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REVIEW

Benefits associated with the implementation of biological control programmes in Latin America

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Abstract Agriculture in Latin America plays a significant role in the region's economy, food security, and rural development. Although pest control has traditionally relied on chemicals, there is increasing adoption of sustainable agricultural practices. Thus, in recent years, there has been a growing emphasis on sustainable agriculture practices, including biological control, to minimise environmental impact, conserve natural resources, and ensure long-term agricultural productivity. In Latin America, high biodiversity enhances biological control, both classical and augmentative biological control. The use of biological control agents allows farmers to produce their crops whilst reducing the use of chemicals in agriculture. In addition, biological control opens new market opportunities for farmers and job options for youth in rural areas. Maximal benefits will however be attained only after adoption of biological control practices and when an effective interaction among key stakeholders is achieved. Thus, farmers and consumers can reap the benefits of biological control, which can incentivise and accelerate adoption at the field level. To evaluate the socio-economic benefits of biological control, establishing multidisciplinary teams to conduct the studies is crucial. The current article explores the benefits resulting from the implementation of biological control programmes, highlighting social benefits. In addition, as part of the Plantwise programme, created to assist agricultural production with a sustainable perspective, data on the use of biopesticides in some countries are discussed in the context of sustainable production looking forward to reinforcing food security and safety in Latin America.

Keywords Benefits · Biological control · Integrated pest management · Sustainable production · Food security · Latin America

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Introduction

Latin America is a geopolitical region that includes more than 40 countries and territories from Mexico to Cape Horn and most of the Caribbean Islands. The region can be subdivided into four geographic areas: South America, Central America, Mexico, and the Caribbean. Latin America is known for its diverse agricultural production (including forestry), which has grown by an average of 2.7% per year over the past two decades. However, chemical compounds are widely used in the region for pest and pathogen control (OECD/Food and Agriculture

Organisation of the United Nations 2019). At high exposure levels, the indiscriminate use of chemical pesticides can cause adverse effects on humans and/or ecosystems. Furthermore, synthetic and potentially harmful pesticides are of particular concern because of their persistence, toxicity, and bioaccumulation properties, which can have adverse ecological effects, causing both short-term (acute) and long-term (chronic), lethal or sub-lethal biological damage (Kim et al. 2017). In this context, the effects on productivity, biodiversity, and farmers' responses should be explored to define effective actions (Silva et al. 2022).

While chemical control is an important component of pest management, the adoption of sustainable agricultural practices in Latin America is often a viable alternative. These include using Integrated Pest Management (IPM) approaches, thus promoting the judicious and responsible use of pesticides, reducing their environmental impact, and preserving natural resources (Deguine et al. 2021). IPM approaches fall within the concept of the Human Right to Food, which seeks to guarantee that the entire food process is socially and environmentally sustainable for the entire population, with the consumption of adequate, healthy (innocuous), nutritious, and culturally-acceptable food (Organisation for the Human Right to Adequate Food and Nutrition 2020).

Biological control is a key component of IPM and involves the use of natural enemies such as predators, parasitoids (macroorganisms), and pathogens (microorganisms) to manage pest populations. This strategy involves selecting and/or releasing specific organisms that prey upon (or parasitise) the target pests, thereby controlling their numbers and limiting the damage to crops, livestock, or other affected entities (Colmenarez et al. 2020; van Lenteren et al. 2020). Classical biological control involves the introduction of species to establish self-propagating populations, while inoculative biological control involves the periodic release of large numbers of commercially produced species (Bale et al. 2008). Research has demonstrated that biological control provides an essential ecosystem service valued at more than $US 400 billion per year globally (Costanza et al. 1997). Biological control contributes to reducing the use of pesticides. Consequently, biological control is a more environmentally friendly, sustainable and cost-effective approach than traditional chemical methods (Bale et al. 2008).

Biopesticides are living microorganisms, microscopic animals (nematodes) and natural products derived from these organisms which only inflict damage on harm-causing pests (Meena and Mishra 2020; Samada and Tambunan 2020). The term "bioproducts" refers to agricultural inputs such as enzymes, extracts (obtained from plants or microorganisms), microorganisms, macroorganisms (invertebrates), secondary metabolites, and pheromones obtained through agro-industrial processes (Ferreira et al. 2021).

Several examples of the benefits of biological control (i.e., pest control, ecological, reduction in pesticide residues, social, and economic) are available in the scientific literature (van Lenteren et al. 2018; Dunn et al. 2020; Palmieri et al. 2022). Maximal benefits will however be attained only after adoption of biological control practices and when an effective interaction among key stakeholders is achieved (Naranjo et al. 2015). One of the main limitations to higher uptake of biological control is insufficient engagement and communication of the considerable benefits of biological control. Therefore, it is crucial to improve communication of economic, environmental, and social successes and benefits of biological control, targeting politicians, decision makers, regulators, growers/land managers and other key stakeholders (Barratt et al. 2018). Better communication of the benefits obtained with the implementation of biological control programmes can help to create incentives and initiatives that can favour the use of biological control (Zhang and Chaudhary 2021). However, there are few publications on the social and economic benefits resulting from the implementation of biological control programmes in Latin America. This can lead to a misunderstanding of the real value associated with biological control and also can cause complications for decision-makers and financial institutions providing incentives and credits to farmers for green technologies (Bale et al. 2008).

According to Zhang and Chaudhary (2021), it is crucial to work within a multidisciplinary context, since the contribution of the scientific community is important to ensure that any ensuing studies include appropriate methodologies to capture the diverse benefits arising from biological control. An ecologist can, for example, contribute to ecological understanding of interactions between pests, natural enemies, crops, and the surrounding ecosystem. In parallel, the participation of an economist to evaluate the economic viability of implementing biological control programmes and the expected socio-economic benefits is important. So, agricultural experts can assess the compatibility of biological control methods with existing agricultural practices and identify potential opportunities for improved crop-production practices. In addition, statisticians and data analysts can contribute to experimental design, data-collection methods, and statistical modelling to ensure robust and reliable assessments of programme effectiveness. Finally, social scientists and policy experts can evaluate the social acceptance and adoption of biological control methods by assessing the perceptions and attitudes of farmers, consumers, and other stakeholders to identify potential barriers or opportunities for implementing biological control programmes. They can also provide insights into policy frameworks and regulatory aspects related to biological control.

Mason et al. (2023) stated that free use and exchange of biological control genetic resources promoted by some countries have provided benefits to the global community, including to both providers and recipients of the agents. Furthermore, restrictive regulations in other countries have however impeded biological control implementation. Linked to this is a need to increase understanding of how the implementation of Access and Benefit Sharing (ABS) regulations and measures impact access to and use of biological control genetic resources that will enable researchers and practitioners, and encourage national governments to consider the positive contribution of biological control to the global community.

In a practical context, the greater adoption of biological control at the field level will require that farmers are familiar with the biological control agents, their use and the technology of release in the context of IPM, in addition to access to a suitable advisory service (Colmenarez et al. 2016, 2020), being paid service or provided by the government. The technology transfer of knowledge and procedures related to biological control require a certain sensitivity as some extension officers have limited knowledge and skills on these practices to serve as a link between researchers and producers (Barrera and López-Arroyo 2007). One example is the Plantwise programme, operated by CABI, created to assist agricultural production with a sustainable perspective, where the main goal is the reduction of pesticides and their substitution by environmentally friendly solutions (including the use of biological control) (https://www.cabi.org/plantwiseplus/). Thus, in this article, some of the key initiatives and efforts at the national and regional level to incentivise and reinforce the uptake of biological control in Latin America are discussed. Benefits resulting from the implementation of biological control programmes are presented, highlighting the social benefits, and data on the use of biopesticides in some countries are discussed within the context of increasing sustainable production and reinforcing food security in Latin America.

Initiatives favouring the uptake of biological control in Latin America

Growing market and increased use of biopesticides

As part of a global expansion of biopesticides over conventional pesticides, the global biopesticides market exceeded $US 4 billion at the beginning of the current decade, and expected to double by the year 2025, with biopesticides comprising approximately half of the total biopesticide share (Rakshit et al. 2021). In line with this, more than 1400 biopesticide registrations have been made worldwide (Wilson et al. 2013; Balog et al. 2017), although, a much lower number of registrations have occurred in Europe due to the complex regulatory system in the European Union. It is expected that the use of biopesticides will continue to increase globally by around 10% each year, with the largest biopesticide market in North America, followed by the European Union and Oceania, South America and Asia (Samada and Tambunan 2020; Kumar et al. 2021). Moreover, biopesticides are expected to take a larger market share as our population and its demand for food grow and the desire to reduce the overall-reliance on chemical pesticides keeps pace (Kumar et al. 2021).

The economic development of the biopesticide market is likely related to (1) the development of pathogen- and pest-resistance to conventional chemical pesticides as well as a decline in the rate of discovery, development, and registration of novel active ingredients with new modes of action; (2) the societal and regulatory pressures to reduce the pesticide residues in food and the environment; and (3) the increased role of IPM in several countries (Sessitsch et al. 2018; Borges et al. 2021). Advances will however be necessary in terms of prospecting for new biopesticides, understanding their mode of action, compatibilities, new formulations, exploration of metabolites, providing technical recommendations, and food and environmental safety (Mazaro et al. 2022). The development of a greater number of bioproducts will make it easier for farmers to access and then understand the benefits on their pest control, thus reinforcing the uptake of sustainable production in crops of economic importance.

Commercialisation and distribution of invertebrate natural enemies

Biological control has frequently been proven to be an efficient and sustainable method of control but the commercialisation and distribution of natural enemies is a determining factor for its adoption by farmers, as is access to suitable advisory services (Colmenarez et al. 2020). It is beneficial to involve farmers in discussions about the recommended practices, including application technology of biological control agents to ensure a high adoption level and the correct use in the field (Colmenarez et al. 2020). The growing use of biological control strategies requires legislative, technical, and cultural changes, to address challenges presented by the diverse stakeholder sectors involved. All are linked to changes in the attitude of the farmers, supported by technical assistance and agronomic consulting services that provide guidelines and recommendations that help the farmer recognise this strategy as an efficacious and easily-applied method once they have understood suitable management practices when using living organisms (Mazaro et al. 2022). Several factors however hinder the implementation of biological control more broadly. The greater communicative power and well-established connection to farmers of the pesticide industry is one of the most important constraints. Others include the negative effect of chemical pesticides on biological and natural pest control resulting from lack of knowledge of how to apply biological control agents, along with an expensive, time-consuming regulatory framework (van Lenteren and Cock 2020), which directly affects the number of biological control products available in national and local markets. The risks of introducing new organisms into new areas for biological control clearly need to be carefully assessed to avoid adverse impacts, though there are now excellent internationally applicable guidelines and models to follow which have been adopted in countries where regulation of biological control is working well. Additionally, it is essential to strike a realistic balance between being cautious about the risks posed by biological control agents and the very real risks associated with alternatives or inaction, particularly in the context of ensuring future food security and maintaining environmental integrity (Barrat et al. 2018).

A further complexity is that while the free use and exchange of biological control genetic resources promoted by some countries has provided benefits to the global community, including to both providers and recipients of the agents, stringent regulations in other countries have impeded biological control implementation (Mason et al 2023). There is therefore a need to increase understanding of how the implementation of ABS regulations and how measures impacting access to the use of biological control genetic resources will enable researchers and practitioners to encourage national governments to consider the positive contribution of biological control to the global community.

An analysis of the list of bioproducts registered and published by the National Plant Protection Organisations (NPPOs) in some Latin American countries revealed that the number of registered bioproducts is growing, with a higher number of microorganism-based biopesticides, mainly in Brazil (233 bioproducts), Colombia (229 bioproducts), and Peru (120 bioproducts). In Chile and Costa Rica, the number of biological control agents based on entomophagous arthropods (predators and/or parasitoids) was higher in comparison with the entomopathogens registered in each country. Bolivia presented the lowest number of biological control agents registered in general (nine biological control agents) (Table 1). The recent increase in the number of bioproducts per country could favour the use of biological control, as it can be easily incorporated as part of IPM approaches, once more biological control agents are registered and commercialised in each country.

Interestingly, despite the high volume of pesticides used overall in Latin America, an acceleration of biopesticide product usage has been observed in South America compared to Central America in recent years. The increase is due to a series of innovative pathways for registering new products in several countries, including national programmes to

Table 1 Number of registered and most frequently used bioproducts (microorganisms and invertebrates) in some Latin American countries in 2022. POMS: Plantwise Online Management System

Country	Biological control agent type	Number of registered products	Most frequently used information via POMS
Bolivia	Entomopathogens	8	*Bacillus thuringiensis* var. *kurstaki*; *Trichoderma harzianum*; *Bacillus subtilis* strain QST713; *Metarhizium anisopliae* + *Paecilomyces lilacinus*
	Entomophagous	1	*Trichogramma* sp.
Brazil	Entomopathogens	233	Not available in POMS
	Entomophagous	65	Not available in POMS
Chile	Entomopathogens	58	Not available in POMS
	Entomophagous	60	Not available in POMS
Colombia	Entomopathogens	229	Not available in POMS
	Entomophagous	28	Not available in POMS
Costa Rica	Entomopathogens	27	*Beauveria bassiana*; *Trichoderma* sp.; viruses; *Paecilomyces* sp.; *Pochonia chlamidosporia*
	Entomophagous	44	*Diadegma insularis*; Chrysopids
Peru	Entomopathogens	120	*Bacillus* sp.; *Trichoderma* spp.; *Beauveria* spp.; *Purpureocillium* sp.; *Paecilomyces* sp.; *Metarhizium* sp.; *Streptomyces* sp.; *Pseudomonas* sp.; *Hirsutella* sp.; *Myrothecium* sp.; *Empedobacter* sp.; *Lecanicillium*; *Beauveria* + *Metarhizium*
	Entomophagous	3	*Trichogramma* sp.; Chrysopids; *Ageniaspis* sp.

encourage this pest management approach in Brazil, Argentina, Colombia, and Chile, where the registration process is more straightforward, accessible, cheaper, and prioritised over synthetic pesticides compared to other Latin American countries (Togni et al. 2023).

Global initiatives

The Plantwise programme

Plantwise aims to assist farmers in reducing crop losses through collaboration with national agricultural advisory services and the development of a global network of plant clinics where qualified plant doctors counsel farmers on practical crop management strategies (https://www.cabi.org/plantwiseplus/). The phytosanitary problems that farmers bring to plant clinics are recorded on the Plantwise Online Management System (POMS). The system also captures the recommendations provided to farmers by the plant doctors.

Using POMS data from Bolivia (n = 7846), Peru (n = 2935), Costa Rica (n = 250) and Honduras (n = 217) from January 2012 to December 2018, an analysis was made with the historical data to describe the variation in the recommendations by the agricultural advisors on the use of pesticides in the countries where the Plantwise programme has been established. The trend in the frequency of the use of chemical control in each country was determined by fitting the data to an additive time series model (y(t) = trend + seasonality + noise) using the R programme (R Core Team 2023). Analysis showed a wide variation across these countries after plant clinic implementation. Bolivia tended to decrease the use of pesticides up to 2016. In contrast, the use of sustainable methods of control increased after 2014. The data between years, among other factors, include a restrictive registration process which contributes to the country presenting a limited number of biological control products available at the national and local market (Table 1). This limits the use of biological control as it is not always possible to find the right product for a given crop problem.

In Honduras, a sustained decrease in the use of pesticides has been observed since 2015. This reflects the effect of training provided to the national extension officers during Plantwise implementation, as they became more familiar with sustainable control methods. Despite the increased use of sustainable methods of control after 2013, the fluctuations observed between years are because crops are affected by different phytosanitary problems and depends on the problem. Bioproducts and other sustainable methods of control available at the local markets may be limited. Despite these positive results, the data available in the POMS system related to Honduras stopped in 2018 due to the decrease in the number of consultations in plant clinics caused by a continuous turnover of extension officers that interrupted the plant-clinic services. High turnover presents a challenge to sustainably maintain the number of well-trained extension officers who provide technical assistance to farmers.

In Peru, the frequency of chemical recommendations was lower than more sustainable methods of control (25 *vs*. 125 reported case, respectively). One of the main factors for these positive results is the commitment that the Ministry of Agriculture and the National Institute of Agrarian Innovation (INIA) made to increase the capacity building of the Peruvian scientists and technicians involved in the field activities, especially those focusing on sustainable agricultural practices, where biological control plays an important role. INIA-Peru also works directly with farmers to review the level of adoption of recommended practices to incentivise farmers to become more familiar with IPM and biological control use on their farms. Another positive driver is that INIA-Peru has incorporated the plant clinics and technology transfer modules as part of the annual operation plan of extension officers in the eight agricultural production areas where Plantwise has been implemented. The areas include Cajamarca, Chiclayo, Cusco, Huaral, Huancayo-Huanuco, Puno, Ayacucho, and Saint Martin, covering the key agricultural production sites in the Andean, Amazon, and costal area of the country. In Costa Rica, chemical recommendations remained lower up to 2017 but an increase was observed thereafter (Figs. 1a–d). The emergence of new pests reported in each country also represents a

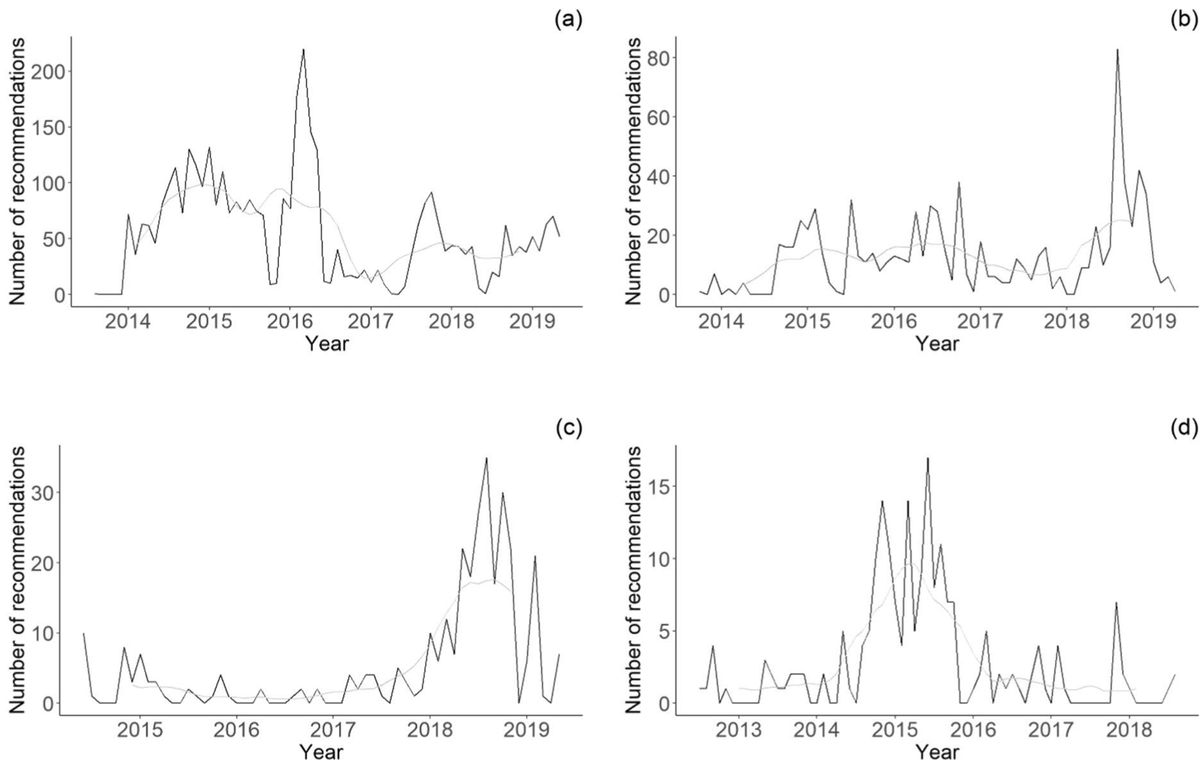

Fig. 1 Number of recommendations of use of chemical pesticides for agricultural pest control in Bolivia (**a**), Peru (**b**), Costa Rica (**c**) and Honduras (**d**). Solid black line shows the absolute number of recommendations given by plant doctors; solid gray line shows the tendency

challenge as there are not always biological control options available to suppress the population of such pests.

In the case of Peru, it was observed that the use of entomophagous control agents increased in the period 2016–2021 (Fig. 2a). The increase could be due to the extension officers' improved familiarity with different biocontrol products available in the country, learned during the Plantwise training courses. It is notable that the entomopathogens were the most common bioproduct recommended in both periods evaluated (2012–2015 and 2016–2021) (Fig. 2b). In Bolivia, the use of entomopathogens declined from 98.98% to 52.67% from the first to the second period evaluated. In contrast, an increase in the use of *Trichogramma* spp. was observed during 2016–2021 compared to the limited use of this parasitoid in 2012–2015. During the implementation of the Plantwise programme, efforts were made to encourage the use of biocontrol products and extension officers were made aware of the different biological control agents available in the country, including *Trichogramma* spp., which is one of the biological control agents with higher mass production and commercialisation at the national level (Franco et al. 2020). Colmenarez et al. (2022) also reported that through the Plantwise programme farmers from Bolivia and Costa Rica were empowered with new environmentally friendly ways of managing pests while maintaining crop productivity, which resulted in the reduction in pesticide use or substitution for less toxic pesticides after the implementation of plant clinics.

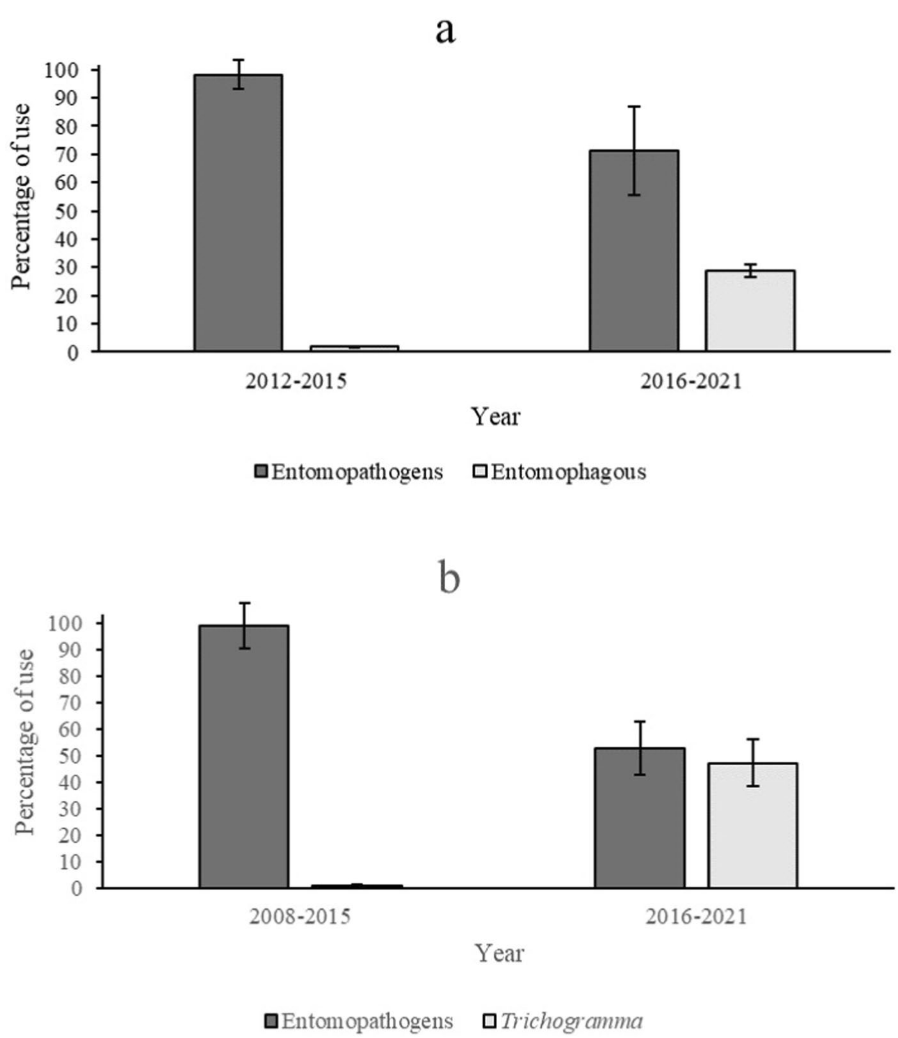

Fig. 2 Percentage of use of entomopathogens and entomophagous (*Trichogramma*) species implemented for biological control in **a** Peru (2012–2021) and **b** Bolivia (2008–2021). Error bars show the standard error (SE)

Another important consideration is the need to provide continuous training to extension officers to ensure they can become more familiar with sustainable practices which can be included in their recommendations to farmers. Unfortunately, in Latin America, the curricula of some universities are lacking in theoretical and practical content related to sustainable agricultural production. Therefore, most agricultural engineers acquire very limited knowledge in terms of biological control practices and other sustainable control methods. Responding to that, working together with universities in Latin America, the Plantwise training content has been incorporated as part of the curricula of some universities in Costa Rica, Nicaragua, Bolivia and Peru, or as part de of specialized training courses on the identification of pests and diseases and sound methods of control, highlighting the use of biological control in the context of IPM (Cartmell 2021).

CABI BioProtection Portal—dissemination of information about bioproducts available in each country

In addition to having more bioproducts registered and commercialised at the national level, it is also vital to disseminate what is available in each country. In this regard, in coordination with the NPPOs, private-sector entities and international and regional organisations, including the International Organisation for Biological and Integrated Control (IOBC), CABI developed the BioProtection Portal (https://bioprotectionportal.com/). The BioProtection Portal is an open-access tool to provide information about registered biological control products in each country to aid farmers, extension officers, students, researchers, consultants and users, in general, to identify, source and correctly apply these products against pests attacking crops.

Regional and national initiatives

A series of conferences organised by the Inter-American Institute for Cooperation in Agriculture (IICA) in 2020 focused on analysing the drivers of augmentative biological control (ABC), highlighting the importance of a favourable policy environment to promote the uptake of ABC in Argentina, Brazil, Colombia, Ecuador, and Mexico (Goulet and Krotsch 2020). According to Buitenhuis et al. (2023), the following key success factors were identified during the conferences: (1) adaptation of regulatory frameworks to facilitate the registration of biological control agents (BCAs) and products, (2) creation of space for commercial biological control manufacturers, thus ensuring a steady supply of BCAs and fostering the growth of the biological control industry, (3) encouragement of safe and good-quality small-scale local production, and (4) active government role in crafting and implementing policies to promote non-chemical pest control.

The Programme for Agroecological Pest Management, developed by the governments of Cuba and Venezuela, stands out as an example of state-supported mass-rearing of natural enemies where a web of Centres for the Reproduction of Entomophagous and Entomopathogens not only made these countries a showcase for biological control but also inspired similar initiatives in other countries such as Brazil, Mexico, Peru, Thailand, and Vietnam (Vásquez et al. 2020; Buitenhuis et al. 2023). Biological control can be considerably improved by its inclusion in area-wide pest management programmes, such as those supported by the FAO International Atomic Energy Agency (FAO-IAEA) (Hendrichs et al. 2021). These programmes have strengthened natural biological control and reduced insecticide inputs during a 30-year period and restored pollination services worth $US 64.9 million as well as increasing sales of products provided by honeybees (Buitenhuis et al. 2023).

Other relevant initiatives that have reinforced the use of biological control in Latin America are led by the Ministries of Agriculture in Latin America. In Argentina, the Ministry of Agriculture, Livestock and Fisheries (MAGyP), in 2015, launched the “Action Plan for the sector of bioinputs for agricultural use”, which aims to increase the production, uptake appropriate use, and diversity of bioinputs in agriculture. It was established the Advisory Committee on Bioinputs used in Agriculture, “Comité Asesor en Bioinsumos de Uso Agropecuario (CABUA)” and National Division of Bioeconomy, reinforcing the exchange of experiences and information related to biological control among national institutions. In Brazil, the National Bioinputs Programme was launched in 2020 by the Ministry of Agriculture, Livestock and Supply (Mapa), allowing better access to information about biological control products available in the country and incentivising the use of biological control agents (Buitenhuis et al. 2023). In Chile, key institutions of the Ministry of Agriculture, for research, Instituto de Investigaciones Agropecuarias (INIA) and plant protection Servicio Agrícola y Ganadero (SAG) are implementing biological control training courses for the sustainable management of key pests and plant diseases, linking with universities and research institutions to incentivise the use of biological control agents at the national level. Chile and Brazil organised the National Symposium of Biological Control, named Siconbiol in the case of Brazil. In 2019, the first Latin American Symposium of Biological Control took place, opening the opportunities for research collaborations and information exchange on biological control in the region.

Benefits obtained by implementation of biological control programmes

Natural enemies are used differently depending on the target pest, host, environmental conditions, and the pest life cycle. Thus, there are three general approaches to biological control: conservation, classical and augmentative biological control (Jeffers and Chong 2021).

Conservation biological control and associated benefits

Conservation biological control consists of manipulating the habitat, plant diversity, production practices, and pest management practices to increase the population and effectiveness of natural enemies (Jeffers and Chong 2021). Recent evidence has shown consistently positive responses of natural enemies to landscape complexity, with higher natural enemy populations, thus greater natural pest control in complex landscapes compared to simple landscapes (Rusch et al. 2016; Ratto et al. 2022).

Aguilar-Fenollosa et al. (2011) investigated the effect of conservation biological control as an alternative to chemical control of *Tetranychus urticae* Koch (Trombidiformes: Tetranychidae) in clementine mandarins. They found a cost reduction between 44.4 and 74.5%. Moreover, several additional post-hoc analyses of field studies have shown that integrating augmentative biological control (entomophagous) with insecticides or biopesticides can result in positive net gains in crop production (Huang et al. 2022). Based on a thorough accounting of costs and benefits, including the research investment, an *ex-ante* analysis showed that integrated mite (*Tetranychus* spp.) control involving the release of the pesticide-resistant predator mite, *Metaseiulus occidentalis* (Nesbitt) (Mesostigmata: Phytoseiidae) in almonds could help producers that use the programme to save between 60 to 110 \$US ha^{-1} with an annual return on the investment in the research between 280 and 370% (Headley and Hoy 1986, 1987).

Classical biological control and associated benefits

Classical biological control involves the intentional introduction of an exotic natural enemy (biological control agent), usually coevolved with its host, to permanently establish in the introduced area for long-term pest control. This is viewed as the ecological re-establishment of a balance that humans have disturbed (Cotes 2018).

Many examples of successful classical biological control programmes are available in the literature worldwide. In Brazil, the introduction of the encyrtid parasitoid *Ageniaspis citricola* Logvinovskaya (Hymenoptera: Encyrtidae) to control the leafminer, *Phyllocnistis citrella* Stainton (Lepidoptera: Gracillariidae) was initiated by releasing the parasitoids in 67 municipalities in São Paulo in 1998, resulting in the rapid spread of the *A. citricola*, thus diminishing the pest in citrus fields (Parra et al. 2022). Similarly, in 2005, the parasitoid *Tamarixia radiata* (Waterston) (Hymenoptera: Eulophidae) was introduced into Brazil for classical biological control against *Diaphorina citri* Kuwayama (Hemiptera: Liviidae) resulting in up to 80% reduction after 800–3200 parasitoids ha^{-1} were released (Parra et al. 2022). Biological control has also led to the profitable production of citrus around the world and allowed access to vitamin-rich, flavourful citrus fruits for a much larger market. This could not have been achieved without the biological control intervention (Menzler-Hokkanen 2006).

Moreover, considering the economic importance of the South American tomato leaf miner, *Tuta absoluta* (Meryck) (Lepidoptera: Gelechiidae), not only in its origin but also in many of its invaded regions, the value of establishing biological control programmes is evident. Thus, where studies of larval parasitoids such as *Dolichogenidea gelechiidivoris* (Marsh) and *Pseudapanteles dignus* (Muesebeck) (Hymenoptera: Braconidae) and other South American native species are being conducted, they could be considered for classical biological control programmes in newly invaded areas. In particular, *D. gelechiidivoris* is considered the most important parasitoid for natural and augmentative biological control in Colombian tomato crops. In addition, experimental releases of *P. dignus* have shown its efficiency as a biological control of *T. absoluta* in tomato greenhouses in Argentina (Salas Gervassio et al. 2019). Similarly, as reviewed by Colmenarez et al. (2022), combining biological control with other ecosystem-friendly strategies has yielded promising results in Colombia, where combining *A. gelechiivoris* with sex-pheromone traps showed a maximum parasitism rate of 68.75% in *T. absoluta* larvae. Additionally, Salas Gervassio et al. (2019) noted two trichogrammatid egg parasitoids, *Trichogramma minutum* Riley and *Trichogramma pretiosum* Riley (Hymenoptera: Trichogrammatidae) are commercially used in various countries and are considered for use as biological control agents against *T. absoluta*. *Trichogrammatoidea bactrae* Nagaraja (Hymenoptera: Trichogrammatidae), an exotic parasitoid introduced in Argentina, has been shown to be more efficient than *T. pretiosum* and *Trichogramma rojasi* Nagaraja and Nagarkatti (two local species) in parasitising *T. absoluta* eggs.

Classical biological control is currently supported by advanced tools such as DNA analyses to verify species identities and likely geographic area of origin, preservation of natural enemy genetic diversity in quarantine and improved understanding of the interactions between the natural enemy and target pest microbiomes. This combined with climate matching and ecological niche modelling help to maximise establishment likelihoods for natural enemies (Hoddle et al. 2015). These authors used citrus scale, *Coccus pseudomagnoliarum* (Kuwana) (Hemiptera: Coccidae), an invasive legacy pest of California citrus in the USA, to demonstrate the potential of new tools to support a new classical biological control programme targeting this insect.

Augmentative biological control and associated benefits

Augmentative biological control refers to the intentional release of mass-reared biological control agents, temporarily augmenting their population densities in a targeted area (Stenberg et al. 2021). Although several terms have been employed, such as inundative biological control, inoculative biological control, or augmentative biological control, the latter is frequently used in the literature because the other options are potentially confusing and have been used in inconsistent ways (Stenberg et al. 2021). According to van Lenteren and Cock (2020), although all forms of biological control and types of biological control agents are used in Latin America, there has been a considerable increase in the area under augmentative biological control from 4,350,000 ha in 17 countries to 31,381,131 ha in 27 countries from 1970 to 2018. Areas under augmentative biological control are usually better documented than those under classical biological control, both for the world and for Latin America and the Caribbean. When data for Latin America are compared with information about the worldwide use of augmentative control, it is evident that its use is by far the largest in Latin America, where there are major augmentative projects (> 100,000 ha under biological control in each project), mainly in Brazil (van Lenteren and Cock 2020). These include millions of hectares of Asian citrus psyllid in citrus, coffee berry borer in coffee, lepidopterans and soil-borne nematodes in maize, cotton bollworm in cotton, and in Bolivia, Brazil, Cuba, millions of hectares of hemipterans and lepidopterans in soybean (van Lenteren and Cock 2020).

Biodiversity preservation and ecosystem services

Several examples of the benefits of biological control (i.e., pest control, ecological, diminished pesticide residues, social, and economics) are available in the scientific literature. In van Lenteren et al. (2021), 21 successful case studies of biological control in Latin America are documented. Table 2 shows some of the most relevant cases. Firstly, environmental benefits are obtained from syrphid flies since they contribute to agroecosystem services through supporting roles as crop pollinators (adults show high floral-visitation rates and pollen-carrying capacity) and as predators

Table 2 Some examples of successful biological control of arthropod pests in Latin America (from van Lenteren et al. 2021)

Case study	Target pest	Biological control agent	Method	Impact
1	Sugarcane borers	*Cotesia flavipes* Cameron (Hymenoptera: Braconidae)	Augmentative and importation	Significant reduction in pest populations and increased crop yield This biological control programme is the largest augmentative arthropod control project in Latin America (3.7 million ha of sugarcane treated with this parasitoid)
2	Coffee berry borer, *Hypothenemus hampei* (Ferrari) (Coleoptera: Curculionidae)	*Cephalonomia stephanoderis* Betrem, *Prorops nasuta* Waterston (Hymenoptera: Bethylidae) and *Phymastichus coffea* LaSalle (Hymenoptera: Eulophidae) Native strains of *Beauveria bassiana and Hirsutella eleutherathorum*	Importation and augmentative	Reduced pest populations from 30–80% and increased coffee production
3	*Anticarsia gemmatalis* Hübner (Lepidoptera: Erebidae) *Nezara viridula* (L.) (Hemiptera: Pentatomidae)	Using the baculovirus AgMNPV Releasing several egg parasitoids: *Telenomus* and *Trissolcus* spp. spp. (Hymenoptera: Scelionidae), *Trichogramma* spp. (Hymenoptera: Trichogrammatidae)	Augmentative and importation; Conservation	Biological control on ~ 700 000 ha in Brazil and ~ 50 ha in Uruguay Commercial product based on *Trichogramma pretiosum* is being applied for control of *A. gemmatalis*, *Rachiplusia nu* (Guenée) (Lepidoptera: Noctuidae) and *Crocidosema aporema* (Walsingham) (Lepidoptera: Tortricidae) with good results
4	*Phthorimaea operculella* (Zeller), *Symmetrischema tangolias* (Gyen) (Lepidoptera: Gelechiidae), *Premnotrypes latithorax* (Pierce), *Rhigopsidius tucumanus* Heller and *Phyrdenus* sp. (Coleoptera: Curculionidae)	*Phthorimaea operculella* granulovirus (PhopGV), Betabaculovirus (Baculoviridae), The parasitoid *Copidosoma* sp. (Hymenoptera: Encyrtidae)	Augmentative and importation	Reduction of *P. operculella* populations by 90%, mainly due to the action of the baculovirus
5	Cassava mealybug, *Phenacoccus manihoti* Matile-Ferrero (Hemiptera: Pseudococcidae)	*Anagyrus diversicornis* (Howard), *Acerophagus coccois* Smith and *Aenasius vexans* Kerrich (Hymenoptyera: Encyrtidae)	Importation	A. *diversicornis, A. coccois* established and dispersed over hundreds of km The three introduced species together with the local native natural enemies resulted in effective control of *P. herreni*
6	Citrus psyllid, *Diaphorina citri* Kuwayama (Hemiptera: Liviidae)	*Tamarixia radiata* (Waterston) (Hymenoptera: Eulophidae)	Importation	Significant reduction in pest populations and increased citrus production The percentage of bacteria-infected psyllids is reduced by 80%

Table 2 (continued)

Case study	Target pest	Biological control agent	Method	Impact
7	Papaya mealybug, *Paracoccus marginatus* Williams (Hemiptera: Pseudococcidae)	*Acerophagus papayae* Noyes and Schauff (Hymenoptera: Encyrtidae)	Importation	In the Caribbean, parasitism resulted in pest population reductions of 82–97%
8	*Maconellicoccus hirsutus* (Green) (Hemiptera: Pseudococcidae)	Two parasitoids: *Anagyrus kamali Moursi* and *Gyranusoidea indica* Shafee, Alam and Agarwal (Hymenoptera: Encyrtidae), and the predator *Cryptolaemus montrouzieri* Mulsant (Coleoptera: Coccinellidae)	Importation	Introduction of these natural enemies provide a good level of control of the pest in the Caribbean
9	Banana weevil borer *Cosmopolites sordidus* (Germar) (Coleoptera: Curculionidae)	Fungi: *Beauveria* spp. (Hypocreales: Cordycipitaceae), *Pochonia chlamydosporia* (Hypocreales: Clavicipitaceae) Entomopathogenic nematodes: *Heterorhabditis* sp. (Nematoda: Heterorhabditidae) and *Steinernema* sp. (Nematoda: Steinernematidae)	Augmentative	*B. bassiana* has shown ~ 77% mortality
10	*Helicoverpa* spp., *Copitarsia turbata* (Herrich-Schäffer), *C. consueta* (Walker), and *C. incommoda* (Walker) (Lepidoptera: Noctuidae) The quinoa moth complex, *Eurysacca melanocampta* Meyrick and *E. quinoae* Pavolnii (Lepidoptera: Gelechiidae)	Several natural enemies (tachinid and hymenopteran parasitoids, as well as predators) *Bacillus thuringiensis*, Nucleopolyhedrosis virus (NPV)	Natural and augmentative	Natural enemies may reach up to 60% population reduction of the pests In Peru, through the so-called Green Farm Certification and Plan Quinoa

of pests (larvae are natural biological control agents, reducing aphid populations) (Dunn et al. 2020).

The maximisation of this ecosystem service requires identifying the factors driving the abundance of natural enemies and pests and the effectiveness of pest suppression in crop fields to design and manage agricultural landscapes (Gurr et al. 2017; Haan et al. 2020). Apart from ecological benefits, biological control also brings economic benefits to landholders, such as lower production costs, increased yield, maintained or greater market access, and higher prices. Therefore, careful economic evaluation of conservation biological control is needed to determine the economic benefits to individual farmers, regions, or agricultural sectors (Cullen et al. 2008).

Reduction of pesticide residue and the resulting effect on human health and expected wellbeing

Another relevant benefit of biological control is the health of farmers and consumers due to the reduction of pesticide residues in products. Palmieri et al. (2022) found that the level of residues detected in fruit treated with fungicides applied at full dose was much higher than that detected in the fruit from plants subjected to biological or integrated strategies, addressing the problems of food security and consumer health and safety related to the toxicity of fungicide residues. Accordingly, rapid growth in the use of biological control is taking place in Latin America because biopesticides are not only healthier for the producers and persons living in farming communities but also are not phytotoxic to plants, ensuring better yields and healthier products with reduced pesticide residues, which benefit the consumer and communities in general (van Lenteren et al. 2018).

Originally intended to emphasise the value of ecosystems and the ecological processes that occur within them for human society and welfare, the Ecosystem Service (ES) concept is now understood as the many advantages that people receive from ecosystems, and is incorporated into policies on biodiversity and sustainability (Bengtsson 2015). Some examples of these services include high production levels, provision of clean air and water, cultural or aesthetic values, and the maintenance of biodiversity, which is tightly associated with biological control of pests, diseases, and weeds in both managed and natural systems (Fiedler et al. 2008). For maximum use of ecosystem services, it is however essential to have comprehensive engagement with stakeholders and rights holders (Loos et al. 2023). This opens the door for innovative ecosystem service assessments, management, and research that can inform and build governance frameworks that support human agency to sustainably identify, manage, and make use of ecosystem services for human wellbeing (Loos et al. 2023).

Social-economic benefits and soil health sustainability

One of the most relevant examples of the social impact of biological control is given by Menzler-Hokkanen (2006), using the California citrus industry in the USA after the invasion of the cottony cushion scale, *Icerya purchasi* Maskell (Hemiptera: Monophlebidae), an exotic pest which devasted the young citrus industry. The first strategy attempted was the fumigation with hydrocyanic-acid gas, with obvious hazards and little effect on the pest. As a result, classical biological control by introducing the ladybird beetle, *Rodolia cardinalis* (Mulsant) (Coleoptera: Coccinellidae), was attempted, the first example of a successful and sustainable classical biological control programme.

In addition, microbe species have been reported to deliver environmental services for soil rehabilitation which are less costly, easier to employ, and more environmentally friendly than other methods. If beneficial microbes such as *Trichoderma* spp. (Hypocreaceae) are combined with conservation agriculture practices such as minimum tillage, emission of green house gases (GHGs) can be reduced at the same time agricultural production is enhanced (Harman et al. 2021). The literature has shown that *Trichoderma* is well known as one of the most valuable biological control agents against several phytopathogens. Hence, managing phytopathogenic fungi using *Trichoderma* spp. has become a sustainable and ecologically friendly strategy that reduces the harmful presence of pathogens in soil, roots and aerial parts of plants (González et al. 2023). For example, in Brazil, there are more than 200 *Trichoderma*-based biofungicides that are used to promote growth and control diseases in soybean, cotton, corn, bean, strawberry, citrus, sugarcane, coffee, tobacco, vegetables, ornamental, fruit and forest species (Bettiol et al. 2019). Similarly, *Beauveria* spp. (Cordycipitaceae) are entomopathogenic fungi recognised as the most important biological control agents for a wide range of agricultural, forestry, and veterinary arthropod pests (Soth et al. 2022).

There remains a need however to increase local capacity to ensure that farmers can get the technical assistance from well-trained extension personnel, which includes biological and other methods of sustainable control, as part of their recommendations to growers (Castillo 2020; Parra et al. 2022). In Brazil, the production of microorganism-based biopesticides by growers for their own use is a practice known as "on-farm production" as part of pest management in perennial and semi-perennial crops and, more recently, it has been extended to pests of annual crops such as maize, cotton, and soybean, and millions of hectares are currently treated with these on-farm preparations (Faria et al. 2023). These biopesticides are predominantly formulated from bacteria, especially *Bacillus thuringiensis* Berliner (Bacilliaceae), targeting lepidopteran pests but there has also been a rapid growth in the production of entomopathogenic fungi, mainly for the control of sap-sucking insects such as the whitefly, *Bemisia tabaci* (Gennadius) (Hemiptera: Aleyrodidae), and the corn leafhopper, *Dalbulus maidis* (DeLong and Wolcott) (Hemiptera: Cicadellidae) (Faria et al. 2023). Local production reduces costs, meets local needs, and reduces inputs of environmentally damaging chemical pesticides, facilitating the establishment of more sustainable agroecosystems.

In Mexico, for example, El Colegio de la Frontera Sur (ECOSUR), in collaboration with other institutions, such as the Autonomous University of Chiapas, and non-governmental organisations, such as Conservation International and Aires de Cambio S.C., are training farmer promoters from the same communities, using the principles of "learning by doing" and "learning to teach", to provide them technical assistance services and training on biological control. This provides opportunities for youth living in rural communities to work as promoters, encouraging the use of biological control at the field level (Barrera and López-Arroyo 2007). In Nicaragua, it is common to find biofactories mass producing natural enemies, run by young entrepreneurs from the local universities, which provide advice on quality control, favouring the commercialisation and distribution of biological control agents. At the same time, some of these small biofactories offer pest monitoring and decision-making services facilitating the adoption of biological control at the field level (Castillo 2020). This activity contributes to ensuring that youth entrepreneurs stay working in rural areas and secure a job which helps to improve their living conditions and favour the adoption of biological control. In Costa Rica, many biological control projects are carried out to support the development and production of entomopathogenic fungi by small providers. Additionally, the majority of exporting companies of fruit, flowers, cotton, coffee and others crops have implemented IPM practices and have laboratories and trained professionals for the production and use of entomopathogens, parasitoids and predators (Faria et al. 2023). This implementation opens new job opportunities for farmers in the country and helps the rural communities have a healthier environment with less pesticide exposure and associated risks.

The economic and social benefits derived from biological control require that new technologies or agricultural practices are created, encouraging farmers to promote what they learn and put the techniques into practice, allowing farmers to reduce adoption barriers such as uncertainty, low trialability, unacceptable risk, or a lengthy wait before benefits materialise (Cullen et al. 2008). However, according to Ratto et al. (2022), although a wide variety of agroecological and socio-economic metrics were used as indicators of biological control success, social evaluations were seldom integrated. In this context, only nine out of 174 studies evaluated both biophysical and social measures. In Brazil and Chile, Polanczyk and Pratissoli (2009) pointed out that the biological control programmes against wheat aphids which, in addition to targeting crucial food crops, also emphasised building local capacity to implement pest management programmes, encouraging the use of simple and low-cost techniques that are easily adapted by small farmers. In addition, Ba et al. (2013) combined an agroecological assessment of the augmentative release of parasitoids to control the millet head miner with structured questionnaires to farmers to assess their perception and knowledge of biological control before and after the study. The researchers observed that improved knowledge by farmers and their willingness to implement augmentative interventions on their farms showed the potential of involving farmers throughout the process to increase their awareness of pests and their natural enemies, as well as their likelihood to adopt biological control interventions.

The use of biological control agents offers farmers access to new markets and job opportunities for young people in rural areas (Barrera and López-Arroyo 2007; Lengai et al. 2022) and enables farmers to produce their crops with fewer pesticides (Colmenarez et al. 2022), avoiding the risks associated with overusing them. This implementation helps rural communities to access unpolluted natural resources such as water from the rivers and natural reservoirs, among other benefits.

Conclusions

In Latin America, biological control has been shown to be a strategy resilient to challenges associated with balancing sustainable food production with healthy ecosystems, providing benefits ranging from economic to social and ecological when suitably adopted. Biological control can therefore be a cost-effective alternative to traditional pest control methods, including situations where other control methods are not allowed or economically feasible. This is particularly relevant in developing countries, such as Latin American countries, where farmers may have limited access to high-quality pesticides and the necessary training and personal protective equipment for their use. Above and beyond this, biological control can create employment opportunities in developing countries through the production and distribution of biological control agents. Biological control can also reduce the risk of resistance development, especially when employed within an IPM strategy that combines different control measures and it can additionally provide monetary benefits through natural pest control services within agroecosystems. Finally, since biological control is a sustainable and ecologically friendly method of control, it can allow farmers access to higher-value markets, such as organic produce requiring more stringent product standards.

However there remain some obstacles that limit the uptake of biological control, such as risk aversity and cumbersome regulatory processes, increasingly bureaucratic barriers to access biological control agents, and insufficient engagement and communication with the public, stakeholders, growers, and politicians of the considerable socio-economic benefits of biological control. The fact that the regulatory processes vary from one country to another will affect the number of bioproducts available in a country and the commercialisation and use of biological control. Furthermore, a lack of documentation for some successfully implemented biological control programmes limits the incentive for farmers to use biological control as a key component of IPM to manage pests. This may arise due to a lack of scientific studies or research conducted on specific biological control programmes because of limited funding or resources allocated to studying and documenting the effectiveness and outcomes of these programmes. Additionally, private companies that develop and use biological control agents, may be reluctant to share detailed information about their programmes to protect commercial interests.

It is very important to ensure that farmers have adequate access to advisory services that enable them to select the correct biological control agent and apply the appropriate application technology as part of the IPM practices applied at the field level. The proper documentation of the social-economic benefits obtained from using biological control in Latin America is crucial to expand the limited information currently available. This can contribute to decision-making at a political and management level to encourage the implementation of new initiatives on sustainable production and allocate funds to favour the use of biological control. Additionally, the banks and financial entities offering credits to farmers will obtain valuable information based on the clear benefits shown, increasing credits delivered to producers for the use of green technology or to small companies for the establishment of bioproduction units for the mass production and commercialisation of biological control agents.

Assessing the impact of biological control programmes requires a multidisciplinary approach due to the complex nature of ecological interactions and the diverse factors involved. Multidisciplinary teams, including ecologists, agricultural experts, economists, statisticians and data analysts, social scientists, and policy experts, among others, are essential to ensure and measure the benefits associated with implementation of biological control programmes. Key benefits will favour humanity in general, providing a healthier environment and contribute to safer and more nutritious food reaching markets. It also enables access to markets and new jobs, improving the living conditions of farmers and youth in rural communities. Finally, the adoption of biological control at the field level will reinforce food security and sustainable production in Latin America.

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Declarations

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