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Contributions of integrated aflatoxin management strategies to achieve the sustainable development goals in various African countries

Alejandro Ortega-Beltran, Ranajit Bandyopadhyay *

International Institute of Tropical Agriculture, Ibadan, Nigeria

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ABSTRACT

In 2015, all United Nations Member States adopted the 2030 Agenda for Sustainable Development to achieve peace and prosperity for all people in the planet. Meeting that ambitious agenda depends on fulfilling all objectives of 17 Sustainable Development Goals (SDGs). Multiple approaches by diverse actors, many of them interconnected, will allow achieving each SDG. However, with compromised food security and food safety, many SDGs will not be realized. In sub-Saharan Africa (SSA), maize and groundnut are two staple crops frequently contaminated with aflatoxins, which threaten food security and food safety. Aflatoxins are extremely dangerous compounds produced primarily by the fungus *Aspergillus flavus*. Even at minute concentrations, aflatoxins negatively influence health, income, and trade sectors. Farmers, traders, industries, and consumers become affected. However, practical solutions exist. Non-aflatoxin producing isolates (referred to as atoxigenic) of *A. flavus* can decrease crop aflatoxin content when used in biocontrol formulations to competitively displace aflatoxin producers during crop development. Typically, treated crops contain 80%–100% less aflatoxin than non-treated crops. The technology was developed by USDA-ARS for use in the US and has been adapted and improved for use in SSA where several products under the tradename Aflasafe are available. There are biocontrol products registered for use in 10 SSA countries and more are being developed. On the other hand, although highly effective, biocontrol is not a panacea. Less aflatoxin occurs across value chains when biocontrol is combined with other practices. In this review, we discuss how i) aflatoxin biocontrol products are developed, manufactured, licensed, and commercialized, ii) aflatoxin management strategies are designed, and iii) integrated aflatoxin management is or will soon be contributing to achieve, in several countries, many targets of most SDGs. We present integrated aflatoxin management as a model intervention contributing to tackle several challenges impeding prosperity and peace in SSA.

1. Introduction

In 2015, all United Nations Member States adopted the 2030 Agenda for Sustainable Development containing 17 Sustainable Development Goals (SDGs).[1] Realizing each SDG in each Member State is the pathway for consistent peace and prosperity. Broad strategies must be converged to tackle impediments to achieve peace and prosperity: poor health and education, inequality, low economic growth, climate change, and ecosystems' deterioration. Agriculture is linked to most SDGs. Thus, appropriate agro-food systems are critical to achieve the SDGs (Tanumihardjo et al., 2019). Agro-food systems must be tailored to realize maximum crop potentials with the highest possible quality. However, various crops are commonly tainted with natural chemicals, including multiple mycotoxins that may occur simultaneously. Of particular relevance are the highly toxic, carcinogenic aflatoxins, which frequently contaminate several crops in the tropics and subtropics (JECFA, 2018). Aflatoxins are among the most toxic substances found in nature. For billions, the food that should provide the required nutrients may be poisonous and causing either chronic or acute symptoms. The United Nations considers exposure to toxic chemicals as a serious violation to the fundamental right to life. Repeated or continuous aflatoxin exposure seriously reduces the chances to have a normal life.

Aflatoxin contamination of staple crops such as maize and groundnut is common across sub-Saharan Africa (SSA) (Shephard, 2008). In SSA, the fungus *Aspergillus flavus* is the most common causal agent of contamination (Atehnkeng et al., 2008; Diedhiou et al., 2011; Probst et al., 2014) although in some cropping systems or certain years other *Aspergillus* species (e.g., *A. parasiticus*, *A. aflatoxiformans*) are major

* Corresponding author.
E-mail address: r.bandyopadhyay@cgiar.org (R. Bandyopadhyay).

[1] https://sustainabledevelopment.un.org.

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contributors to contamination events (Cardwell and Cotty, 2002; Probst et al., 2012; Kachapulula et al., 2017). Among the four major aflatoxins (B_1, B_2, G_1, and G_2), aflatoxin B_1 is the most prevalent and toxic and is a Group 1 carcinogen in the International Agency for Research on Cancer classification system (IARC, 2002). Consumption of foods tainted with aflatoxins poses serious health threats such as stunting, impaired food conversion, immunosuppression, liver cancer, and, depending on the dose and other factors, rapid death can occur (Gieseker, 2004; Liu and Wu, 2010; Chan-Hon-Tong et al., 2013; Kamala et al., 2018). Livestock and fish fed with contaminated feed have reduced productivity and/or increased mortality (Bryden, 2012; Monson et al., 2015; Oliveira and Vasconcelos, 2020). In short, aflatoxin contamination negatively impacts health, income, food safety, and trade sectors (Wu, 2015; Bandyopadhyay et al., 2016; Nelson, 2020). Thus, aflatoxins are a significant barrier to attain the SDGs.

Despite their major negative impacts, aflatoxins are pronouncedly underestimated in the developing world. The toxins cannot be seen or smelled; farmers and consumers typically do not know what aflatoxins are, the burdens they cause, or ways to mitigate them; detection requires laboratory tests not easily accessible; and markets typically do not discriminate crops (Udomkun et al., 2017). In SSA, regulations for aflatoxin – or any food safety parameter – if exist, are poorly enforced. Most crops are consumed without knowing if they are safe, especially those offered in local, unregulated markets due to inappropriate testing infrastructure, local consumption, food scarcity, among other constraints (Bandyopadhyay et al., 2016). To make matters worse, crops tested and rejected oftentimes end up in informal markets or kept by the producers, which causes higher exposure (Matumba et al., 2015a).

Susceptible crops typically become contaminated in the field (Kamika et al., 2016; Mahuku et al., 2019) but aflatoxin levels may increase several folds with deficient post-harvest, storage, and/or transport practices (Waliyar et al., 2015; Seetha et al., 2017; Mahuku et al., 2019). For decades, substantial efforts to develop technologies to control aflatoxin have been conducted (Lillehoj et al., 1980; Jaime-Garcia and Cotty, 2004; Hell et al., 2008; Walker et al., 2018; Pandey et al., 2019). However, most of those tend to be inconsistent, may not prevent field aflatoxin formation or reduce aflatoxins to safe levels, are impractical when crops are already contaminated, or are unavailable to most farmers. Furthermore, valuable technologies are often used in isolation, eroding mitigation efforts. Biotic and abiotic stressors, agronomic and storage practices, climatic conditions, and sociological and institutional challenges contribute to aflatoxin contamination. The complexity of the problem requires holistic interventions at both pre- and post-harvest stages and support by institutional, policy, and sensitization actions (Bandyopadhyay et al., 2016; Ayalew et al., 2017; Logrieco et al., 2018). Thus, for better outcomes, aflatoxin management must be coordinated among farmers, government agencies, donors, researchers, policy makers, and other key stakeholders. Multi-stakeholder-driven approaches may successfully address pressing, complex agricultural problems (Brancalion and Holl, 2020; Evans et al., 2020).

A technology that consistently and effectively reduces aflatoxin content throughout the value chain is, fortunately, available for use in various countries. The United States Department of Agriculture – Agricultural Research Service (USDA–ARS) developed a biocontrol technology based on an atoxigenic (i.e., non-aflatoxin-producer) isolate of *A. flavus*, AF36, that competitively displaces aflatoxin producers during crop development (Cotty et al., 2007). Drastic aflatoxin reductions (up to 100%) occur in treated cottonseed, maize, pistachio, almond, and fig grown in the US compared to untreated crops. AF36 is registered with the US Environmental Protection Agency (USEPA) (Cotty et al., 2007). Another biocontrol product—with a different active ingredient—

registered with USEPA is Afla-Guard®, for use in maize and groundnut in the US (Dorner, 2004).

The International Institute of Tropical Agriculture (IITA), along with USDA–ARS, and national and international institutions, adapted and improved aflatoxin biocontrol initially for use in maize and groundnut in SSA, and recently the crop target is being expanded to include sorghum, sesame, millet, and sunflower. From here on, this multi-partner consortium operating in several SSA countries is referred to as Aflasafe Initiative. Diverse biocontrol products have been developed under the trade name Aflasafe, and each consistently and effectively reduces aflatoxin (up to 100%) (Bandyopadhyay et al., 2019a; Agbetiameh et al., 2020; Senghor et al., 2020). The atoxigenic isolates of *A. flavus* composing Aflasafe products are selected based on their adaptation to target areas and after determining their inability to produce aflatoxins and other mycotoxins [e.g., cyclopiazonic acid (CPA)]. Reviews of the progress, status, challenges, opportunities, and misconceptions of biocontrol in SSA have been made by our group (Bandyopadhyay et al., 2016; Ortega-Beltran and Bandyopadhyay, 2019; Konlambigue et al., 2020; Moral et al., 2020) and others (Pitt 2019; Kagot et al., 2019; Moore 2021).

Smallholder farmers participating in market-based agriculture have access to Aflasafe products when working with public and/or private-sector entities that organize farmers into groups, disburse the biocontrol product and inputs needed to enhance yield and crop quality, and offer training on input usage and other aflatoxin management strategies. The smallholder farmers may pay for the inputs, including the biocontrol product, either fully or partially upon delivery. Farmers who make partial payments reimburse the input costs to the private/public sector entities after aggregation or sale of their crops. In some cases, mostly in subsistence agriculture settings, farmers receive the products free of charge through government relief programs or at low cost as part of input subsidy package of governments.

Although aflatoxin biocontrol is very effective when used correctly at the appropriate time (2-to-3 weeks before crop flowering) and dosage (10 kg/ha), the technology is not a panacea. Using biocontrol with all other available technologies results in less contamination throughout the value chain. Breeding for resistance, biocontrol, insect control, rapid drying, sorting, improved postharvest practices, and other technologies used as an integrated management system have better chances to reduce contamination. Such system requires collective actions by individuals from diverse organizations—many times with multiple interests—, from farmers to Cabinet Ministers.

Despite aflatoxins being typically underestimated in SSA, this is gradually changing. Countries belonging to East African Community (EAC), Common Market for Eastern and Southern Africa (COMESA), and the Economic Community of West African States (ECOWAS) now recognize aflatoxin as a serious impediment to prosperity. Some countries have integrated aflatoxin control into their National Agricultural Investment Plans. Furthermore, several institutions develop, coordinate, and synergize actions to effectively control aflatoxin and reduce exposure. For example, the Partnership for Aflatoxin Control in Africa (PACA) of African Union Commission has as a mandate for the protection of crops, livestock, and people from the effects of aflatoxins to improve food security, health, and trade across Africa.[2] The Aflasafe Initiative works closely with EAC, ECOWAS, and PACA to design management strategies centered on biocontrol and converged with practical pre- and post-harvest technologies, awareness and sensitization campaigns, testing support, market development, dietary and policy interventions. The holistic interventions for aflatoxin mitigation are designed along with relevant stakeholders in a time-sensitive manner to ensure appropriate communication flow, avoid potential misunderstandings, and collectively decide on best ways forward.

In this communication we briefly explain how aflatoxin biocontrol products are developed and commercialized. Then, we enlist the components of aflatoxin management strategies. We then describe how integrated aflatoxin management is or will soon make contributions to fulfill, in several African countries, many targets of most SDGs.

1.1. Aflatoxin biocontrol product development and large-scale use

Considerable efforts are needed to develop, test, register, and make aflatoxin biocontrol products available at scale (Moral et al., 2020; Konlambigue et al., 2020). Here we briefly describe the process followed by the Aflasafe Initiative to make biocontrol available and accessible to smallholder farmers. In Nigeria, the process took well over 10 years. In countries where biocontrol development is at early stages, lessons from Nigeria and other countries (e.g., Senegal, Kenya) are incorporated into the process to drastically cut product availability time. To date, Aflasafe products have been registered for use in Nigeria, Kenya, Senegal, The Gambia, Burkina Faso, Ghana, Tanzania, Zambia, Malawi, and Mozambique (Moral et al., 2020). Efforts to develop products for use in Benin, Burundi, Cameroon, Mali, Niger, Rwanda, South Sudan, Sudan, Togo, Uganda, and Zimbabwe are ongoing. More African countries (e.g., Cote d'Ivoire, Sierra Leone) have expressed interest in biocontrol. In parallel, technologies and infrastructure have been developed to produce biocontrol products at scale. The process is summarized below:

- Awareness raising of key stakeholders (farmers, farmer organizations, private sector, government officers, regulators, researchers, and others) on aflatoxins, their impacts, and available solutions.
- Sample collection (e.g., maize, groundnut, sorghum) to develop baseline information on aflatoxin prevalence across target countries.
- Capacity building of local students, scientists, and key stakeholders.
- Identifying native atoxigenic isolates of *A. flavus* from crops and soils using microbiological, chemical, and molecular techniques.
- Conducting laboratory competition experiments to detect atoxigenic isolates with superior abilities to limit aflatoxin when challenged with highly toxigenic fungi.
- Along with farmers, testing individual atoxigenic isolates in field conditions to identify the most efficient under natural conditions.
- Selecting superior atoxigenic isolates to compose multi-isolate candidate biocontrol products.
- Conducting field effectiveness trials, in hundreds of farmer fields, during multiple years, in multiple agro-ecological zones to test candidate products in diverse environmental and cropping conditions.
- Designing, testing, and validating industrial processes to produce the active ingredient fungi and the biocontrol product *per se.*
- Constructing infrastructure to manufacture aflatoxin biocontrol products.
- Improving the capacity of national regulators on aflatoxin-related matters.
- Preparing dossiers for registration of biocontrol products with national regulators. Dossiers contain effectiveness, toxicological, and eco-toxicological data, product information, instructions, among other data.
- Obtaining regulatory approval for unrestricted biocontrol usage.
- Conducting market analysis and elaborating commercialization options for actors interested in manufacturing and/or distributing biocontrol products.
- Selecting manufacturing and/or distribution partners.
- Providing technical support to manufacturers/distributors of biocontrol.
- Testing the market with partners and demonstrating large-scale impact of biocontrol.
- Continuing supporting partners based on their feedback and that from end-users.

Certainly, this is a short summary of the aflatoxin biocontrol product

[2] https://www.aflatoxinpartnership.org.

development and commercialization process. Some components of the process have been described (Donner et al., 2009; Atehnkeng et al., 2014, 2016; Adhikari et al., 2016; Bandyopadhyay et al., 2016, 2019a; Agbetiameh et al., 2019, 2020; Aikore et al., 2019; Ortega-Beltran et al., 2021a; Senghor et al., 2020) although those publications contain only a fraction of the wealth of field activities and interactions with diverse stakeholders.

1.2. Integrated aflatoxin management

The Aflasafe Initiative designs aflatoxin management strategies centered on biocontrol and tailored to contexts of target countries. Any practical, effective technology/approach available is adopted to synergize their benefits. Implementing tailored management strategies can result in consistent supplies of aflatoxin-compliant crops in an affordable, economic manner. Tailored interventions typically result in crops with >80% less aflatoxins, sometimes 100% less, than untreated crops grown, processed, and stored using traditional practices (Bandyopadhyay et al., 2019a; Agbetiameh et al., 2020; Senghor et al., 2020, 2021). Components of tailored strategies are summarized below.

Awareness and sensitization campaigns. A major impediment for adoption of aflatoxin management strategies across SSA is the low level of awareness among farmers, processors, agricultural and health officers, regulators, and consumers, on aflatoxins and their impact, and control methods (Udomkun et al., 2017). To increase public awareness on aflatoxins it is critical to design sensitization campaigns considering the context of target regions/countries (James et al., 2007) and direct the campaigns to all key stakeholders (Johnson et al., 2015).

During the inception of an aflatoxin mitigation project, regulators and key policy makers are sensitized about aflatoxins, their impact, and management options. This knowledge is then transferred to research partners (universities, agricultural institutes), farmers, and extensionists that help to develop, test, validate, and register biocontrol products with regulatory authorities. After registration, private sector actors are mobilized to receive information on benefits of using treated crops for profitability of their industries [e.g., poultry producers (Aikore et al., 2019);] and be linked to producers of safe crops (Bandyopadhyay et al., 2019a). Private sector actors are also informed about business opportunities to manufacture and distribute biocontrol and possibilities to unlock domestic and foreign premium markets when producing aflatoxin-safe crops.

To tackle aflatoxin unawareness and biocontrol misconceptions, communication campaigns are designed. For example, in Kenya, there have been substantial efforts to disseminate critical information. Most Kenyans residing in aflatoxin-prone areas have heard about aflatoxins but are unaware of their dangers and available management strategies. Since 2014, more than 7000 farmers, 1000 extensionists, and 300 policy makers have been sensitized. In 2017, with support from USAID, a communication strategy was designed to increase awareness across Kenya by disseminating information to farmers, extensionists, agrodealers, agriculture-related ministries, and regulators. The strategy was developed collaboratively with the Kenya Agriculture and Livestock Research Organisation, Ministry of Agriculture, Livestock and Fisheries, National Irrigation Board, Pest Control Products Board, National Cereals and Produce Board, Eastern Africa Grain Council, extensionists, farmer leaders, public health sector, agriculture county directors, and media reporters. Similar efforts have been conducted in Nigeria, Ghana, Burkina Faso, and Tanzania. In addition, the Aflasafe Initiative supported PACA to develop similar strategies at regional and country levels.

Improved pre-harvest practices. Several factors may contribute to increased contamination even before the crop enters its reproductive stage. Prevention of both plant stress and damage are promoted including use of improved seeds, proper land preparation, appropriate planting date, correct spacing, appropriate fertilization, weed control, irrigation whenever possible, and insect control. Those practices are associated with reduced plant stress and insect damage and thus reduced aflatoxin accumulation (Munkvold, 2003; Diao et al., 2014; Seetha et al., 2017; Mahuku et al., 2019).

Use of atoxigenic isolates of *A. flavus* as biocontrol agents. Aflatoxin management strategies designed by the Aflasafe Initiative are centered on biocontrol containing atoxigenic fungi as active ingredient. The fungus *A. flavus* is composed of numerous vegetative compatibility groups (VCGs), which varying in several characteristics, including aflatoxin-producing ability (Leslie, 1993; Grubisha and Cotty, 2010, 2015). Most VCGs are composed of aflatoxin producers (Horn and Dorner, 1999; Mehl et al., 2012; Mauro et al., 2015). Other VCGs are composed of both toxin-producers and atoxigenic members. Some VCGs are composed exclusively of atoxigenic individuals and can be used as biocontrol agents (Dorner, 2004; Mauro et al., 2015; Mehl et al., 2012). Members of widely distributed atoxigenic VCGs across a target country, with superior abilities to reduce aflatoxin in both laboratory and field conditions are selected to constitute biocontrol products (Moral et al., 2020).

Aflatoxin biocontrol is applied before *Aspergillus* populations begin to increase. Natural fungal increases typically occur during crop flowering when crop biomass becomes readily available. Thus, applying atoxigenic fungi 2-to-3 weeks before flowering results in displacement of aflatoxin producers. Because less aflatoxin producers become associated with treated crops, less aflatoxins accumulate, sometimes no aflatoxin at all (Horn et al., 2000; Cotty et al., 2007; Agbetiameh et al., 2020). In addition, biocontrol isolates maintain their association with treated crops at all post-harvest stages, until consumption. Thus, infection by aflatoxin producers and subsequent aflatoxin production is discouraged from field to plate (Bandyopadhyay et al., 2016; Senghor et al., 2020).

Improved harvest and post-harvest practices. Improper harvest and post-harvest practices significantly increase aflatoxin during storage, transport, and until crop consumption (Aidoo, 1993; Hell et al., 2008; Diao et al., 2014; Waliyar et al., 2014; Seetha et al., 2017). Thus, training is given to farmers and/or trainers of farmers to harvest immediately after crops mature. Trainees are sensitized on risks associated with i) early harvesting: high moisture content, increased drying time, and susceptibility to mould growth during storage; and ii) delayed harvesting: quality loss, unnecessary exposure to birds, rodents, and/or rain, which can contribute to increased fungal growth and aflatoxin formation. Harvested crops are recommended to be quickly dried to safe moisture levels, 10–12%.

Maize farmers are advised to avoid harvesting cobs from lodged plants because of likelihood of being in contact with soil residing aflatoxin producers, and to separate healthy ears from immature, insect- or rodent-damaged, and/or diseased cobs. If farmers heap plants to dry, they are advised to maintain the heaps erect, forming a cone, and to avoid big heaps which may fall and/or may accumulate moisture at the center. Other recommendations are to place de-husked cobs into clean bags, avoid contact with the soil, and not to dry cobs on bare soil. Groundnut farmers are advised to avoid damaging the pods when uprooting to prevent predisposition to fungal growth during storage, and to place picked pods into clean containers. Diseased or damaged groundnut are recommended to be separated from healthy produce since even under optimal storage conditions, fungal growth may occur faster in damaged than in intact nuts.

Farmers are advised not to thresh maize by beating it with sticks but to use well-calibrated threshers that maintain good grain integrity. Good sanitation practices are advised as well. Cracks and breaks in groundnut pods occur mainly during shelling, through trampling or inappropriate use of machines. After threshing or shelling, farmers are advised to dry maize and groundnut grains in the sun, either on mats, plastic tarpaulins, raised platforms, or clean cement. Farmers are advised to cover grains with water-proof polyethylene sheets if rainfall is forecasted and to avoid, at all costs, exposure of grains to soil or water.

Sorting. Sorting to remove discolored, damaged, or oddly shaped kernels is emphasized to farmers. Atypical kernels are associated with high aflatoxin content (Pelletier and Reizner, 1992; Matumba et al., 2015b; Aoun et al., 2020). After threshing or shelling, farmers are advised to clean grains, separating whole from broken grains and foreign materials. Winnowing, screening, or sifting, are options given. Advice is given to avoid using grade-out grains for human and/or animal consumption. Grade-out grains are sometimes consumed by the farmers and/or their families or may be sold at local informal markets. Both practices dramatically increase aflatoxin exposure (Kaaya et al., 2006; Matumba et al., 2015a).

Improved storage structures, use of hermetic bags. The type of storage structures largely influences post-harvest aflatoxin content (Aidoo, 1993; Hell et al., 2000). Farmers are advised to utilize well-ventilated structures, with strong, well-built walls and roofs that prevent rain seepage and excess moisture. Farmers are advised to repair, fumigate, and disinfect the structures before storing new harvests. Control of insects and rodents to prevent loss of crop quality and spoilage is emphasized. Use of hermetic bags and silos have been demonstrated to effectively prevent aflatoxin production during storage (Danso et al., 2018, 2019; Walker et al., 2018).

Dietary interventions. Aflatoxin exposure may be reduced when consuming crops with low aflatoxin risk (Hell et al., 2008). Although changing dietary habits may be difficult (food scarcity, high food prices, resilience to change diet type), farmers and value chain actors are encouraged to consume more foods prepared with non-susceptible crops. In both Uganda and Zimbabwe, millets were found to be less susceptible to aflatoxin and other mycotoxins than the most preferred maize and sorghum and the authors recommended greater consumption of millets (Bandyopadhyay et al., 2007; Wokorach et al., 2020; Akello et al., 2021).

Testing. In Nigeria, maize and groundnut farmers using integrated aflatoxin management in commercial crops received aflatoxin testing support by the Aflasafe Initiative (Bandyopadhyay et al., 2019a). Lots of aggregated maize and groundnut (range = 3–31 tons) are randomly sampled (~5 kg) and samples transferred to IITA for aflatoxin quantification. Results are then communicated to farmers/aggregators for them to offer their aflatoxin-compliant crops to high-end processors. The service provided by IITA allows farmers/aggregators to know the type of market they could reach. On many occasions, IITA staff and grain buyers/industries visit warehouses of farmers using integrated aflatoxin management to quantify aflatoxins *in-situ* using USDA/GIPSA-approved quantitative lateral flow immunochromatographic assays (Senghor et al., 2021). Farmers/aggregators who witness and participate in the analysis gain additional confidence in effectiveness of aflatoxin management (Senghor et al., 2021). The Aflasafe Initiative provides testing support, also *in-situ*, in Senegal, Kenya, The Gambia, Burkina Faso, and Ghana, to interested agricultural enterprises. After a testing system has been established, the interested industries adopt the testing system and absorb the costs of the tests and conduct the testing on their own.

Market development. Several barriers impede marketability of both aflatoxin biocontrol and aflatoxin-safe crops, including farmer and consumer awareness about aflatoxins, its impacts, and management options, access to both the product and treated crops, affordability of the product, resilience to adopt new technologies, lack of market discrimination for aflatoxin-safe crops (Johnson et al., 2018). In Nigeria, the AgResults Aflasafe Pilot project created a sustainable demand for both the biocontrol product and aflatoxin-safe crops (Bandyopadhyay et al., 2016, 2019a; Schreurs et al., 2019). The Pilot relied on private and public sector enterprises (known as implementers) that recruited and trained farmers on aflatoxin management centered on biocontrol and provided inputs and services to farmers. After harvest, implementers purchased the maize from their farmers and sought buyers of aflatoxin-compliant maize, who pay premium prices for aflatoxin-safe crops (Bandyopadhyay et al., 2019a; Shenge et al., 2019). Similar models are being implemented in Nigeria, Senegal, Burkina Faso, and The Gambia to produce aflatoxin-safe groundnut targeting international and domestic markets. All learned lessons are adapted to countries where biocontrol is commercially available.

Technology transfer for manufacturing and distribution. After registration, the Aflasafe Initiative, through the Aflasafe Technology Transfer and Commercialization (ATTC) project, licenses biocontrol manufacturing and commercialization responsibilities (Schreurs et al., 2019; Konlambigue et al., 2020). ATTC is the platform for scaling-up biocontrol in several African countries by executing tailored commercialization strategies. Biocontrol can reach millions of farmers by i) registering biocontrol products in more countries; ii) developing and validating country-specific commercialization strategies, developing partnerships with government and private entities interested in manufacturing and distributing biocontrol, and developing and executing technology transfer agreements; and iii) creating demand for aflatoxin-safe products at the end market to stimulate biocontrol uptake by farmers.

In each country, ATTC assesses market projections, determines manufacturing feasibility and distribution scenarios as well as capabilities of potential investors, and determines best practices and interventions to increase biocontrol uptake. After a commercialization strategy is ready, potential investors are invited to attend fora to spark their interest to manufacture and distribute biocontrol. Motivated investors submit an expression of interest and those meeting several criteria are invited to submit a business plan. Then, a Technology Transfer and Licensing Agreement (TTLA) is signed with the selected investor. TTLAs ensure that investors will make enough profits but ensuring that the product will be accessible to smallholder farmers at a reasonable cost as determined in willingness to pay studies (Ayedun et al., 2017; Migwi et al., 2020). ATTC works with each investor to transfer the technology know-how, design awareness-raising strategies using digital and conventional tools, develop training materials, and organize advocacy events to sensitize key stakeholders. To date, manufacturing and distribution agreements with private companies have been signed in Nigeria, Senegal (which covers The Gambia), Tanzania, and Mozambique, and with the Government of Kenya. Distribution agreements with companies in Kenya, Burkina Faso, Ghana, Malawi, Mali, and Mozambique have been signed.

To make biocontrol products available at scale, it is necessary to design, construct, test, and validate appropriate industrial infrastructure. The Aflasafe Initiative constructed a demonstration plant in Ibadan, Nigeria, which was the third aflatoxin biocontrol product manufacturer across the globe and first in Africa (Bandyopadhyay et al., 2016). Using the plant in Ibadan as a model, laboratory and manufacturing facilities of the licensees were designed in Nigeria, Kenya, Senegal, and Tanzania. The Aflasafe Initiative technically backstops partners to ensure correct construction and operation of their facilities. Manufacturing plants of all licensees have evolved by improving the design and processes of the demonstration plant. Lessons from past experiences have helped made better manufacturing plants. Construction of manufacturing plants in Rwanda, DR Congo, Mozambique, Burundi, and Sudan is underway.

Policies. The Aflasafe Initiative aids participating countries to improve their capacity to monitor, regulate, and control aflatoxins. Major emphasis has been placed to develop standards based on dietary habits, awareness among key stakeholders on control strategies and regulations, and reinforcement of food safety risks assessment, inspection, and analysis systems. For example, USAID supported the Aflatoxin Policy and Program for the East Africa Region (APPEAR), implemented by EAC and IITA. The program had as members Ministers of Health, Agriculture and Trade, their Deputies, and key public and private sector actors of EAC. APPEAR produced 11 technical papers to address several topics including pre- and post-harvest technologies, food and feed standards, nutrition, health, communication, biocontrol, trade, and disposal.[3] Once published, the technical papers were subsequently

[3] https://www.eac.int/documents/category/aflatoxin-prevention-and-control.

carried back to the EAC countries for implementation. In West Africa, ECOWAS Parliament is discussing with IITA and other organizations legislative actions for improving food safety across the region, access to quality food within the region, and mutual accountability for actions and results. It is expected that this high-level planning will result in a region-wide food safety agenda.

Novel aflatoxin management tools. Any other technology or activity effective —and applicable to the context of target countries—in limiting contamination and/or aflatoxin exposure is adopted. This occurs regardless of the set of skills, perspectives, or approaches in which those technologies were developed. Since there are no silver bullets to decrease crop aflatoxin content, the Aflasafe Initiative incorporates all environmentally sound, ethical, and appropriate technologies/strategies that may improve aflatoxin management efforts. However, novel tools must be both available and accessible to smallholder farmers.

1.3. *Calls to address the SDGs*

Development of aflatoxin management strategies centered on biocontrol has been possible through funding by different development investors, governments, NGOs, and/or relief programs. Funds from over five sources may be used in each country. Since 2016, proposals to fund agricultural projects require designing projects contributing to achieve one or various SDGs. In addition, programs of the CGIAR System Organization, to which IITA belongs, to be implemented from 2022 onwards will be SDG-oriented. Across SDGs, agriculture-related targets have as a major goal the production of safe and nutritious foods, improve income and livelihoods, and adapt to climate change constraints. Fulfilling those targets will significantly reduce hunger, malnutrition, poverty, unrest, and economic underdevelopment. Recently, Nelson (2020) called for CGIAR programs to tackle several constraints at once, including 'climate, health, sanitation, urban design, aquatic ecology, market systems and most of the other realms of the SDGs'. Since its inception in 2003, the Aflasafe Initiative was designed to address many challenges by converging diverse technical, social, regulatory, and structural solutions. Most of those challenges are also targets of the SDGs.

1.4. *Contributions of integrated aflatoxin management to achieve the SDGs*

Here we describe how integrated aflatoxin management is, or soon will be, helping to achieve several targets (55 at least) of 13 of 17 SDGs in countries where the Aflasafe Initiative operates.

1.5. *Access to natural resources and appropriate new technologies*

Aflatoxin biocontrol products contain beneficial fungi native to target countries (Mehl et al., 2012). Native beneficial fungi are natural resources property of the country of origin and can be used in biocontrol products to mitigate aflatoxin consistently and effectively in maize, groundnut, and other crops. The Aflasafe Initiative makes biocontrol products accessible and available by facilitating manufacturing and commercialization efforts in participating countries.

1.6. *Reduce exposure to climate-related events*

Crops developing during extraordinary heat and drought conditions, as those caused by climate change, tend to accumulate high aflatoxin content (Battilani et al., 2016; Medina et al., 2017). Aflatoxin biocontrol was developed for use in hot agricultural areas of the Southern US desert, where it is highly effective (Cotty et al., 2007; Mehl et al., 2012). In Africa, aflatoxin biocontrol is effective in hot, difficult farming conditions of Senegal (Senghor et al., 2020), Nigeria (Bandyopadhyay et al., 2019a), Ghana (Agbetiameh et al., 2020), The Gambia (Senghor et al., 2021) and several other countries. Safe and nutritious crops can be produced even if grown under climate change challenges.

1.7. *Reduce malnutrition-related disabilities*

Consumption of aflatoxin contaminated crops is linked to malnutrition, immunosuppression, stunting, liver cancer, among other maladies (Wild, 2002; Shirima et al., 2015; Githang'a et al., 2019). Integrated aflatoxin management allows producing safe, nutritious foods and thus can contribute to reduce disabilities caused by malnutrition and diseases associated with aflatoxin exposure (Grace et al., 2015; Wu, 2015).

1.8. *Mobilize resources to implement programs and policies to end poverty*

Development of aflatoxin biocontrol products, their industrial manufacture, and making them commercially available involves substantial resource mobilization (see Acknowledgements). The overall goals of the Aflasafe Initiative are 'Safer crops, better health, and higher income'. Those goals, achieved through large resource mobilization, aid in lifting populations out of poverty through the production, consumption, and commercialization of aflatoxin-safe crops.

1.9. *Create sound policy frameworks to enforce legislation*

The Aflasafe Initiative aids participating countries to improve their capacity to monitor, regulate, and control aflatoxins. Major emphasis has been placed to develop aflatoxin standards based on dietary habits, awareness among key stakeholders on control strategies and regulations, and reinforcement of food safety risks assessment, inspection, and analysis systems. For example, EAC in collaboration with the Aflasafe Initiative has published policy briefs on aflatoxin prevention and control.[4]

1.10. *Access by poor people to safe, nutritious, sufficient food*

Smallholder farmers across Nigeria using integrated aflatoxin management have access to safer crops, crop-derived products, or safe products from livestock fed with aflatoxin-reduced crops. To date, over 300,000 tons of aflatoxin-safe maize have been produced in Nigeria. Most of the safe maize was commercialized in premium markets—and farmers received increased income—and 20%–40% of the maize was kept by the farmers to be consumed by their families (Bandyopadhyay et al., 2019a; Narayan et al., 2019). This substantially reduced aflatoxin exposure of those farmers, their families, and communities accessing the safe maize (Narayan et al., 2019). In addition, farmers obtained higher yields because of use of improved agronomic practices bundled with aflatoxin management. Similar benefits are obtained in other countries (Agbetiameh et al., 2020; Senghor et al., 2020, 2021).

1.11. *Reduce child stunting and wasting*

Aflatoxin exposure may begin in the womb if pregnant women ingest contaminated food (Gong et al., 2008). Children exposure to aflatoxin may continue through contaminated breastmilk and/or weaning foods. It is during the first 1000 days of life when humans suffer more the

[4] https://www.eac.int/documents/category/aflatoxin-prevention-and-control.

aflatoxins' effects, which include stunting, wasting, and underweight (JECFA, 2018). Availability of aflatoxin-safe foods for pregnant mothers and young children is likely to contribute to reduced stunting, wasting, and underweight.

1.12. Address nutritional needs of all people

As mentioned in Target 2.1, 20%–40% of aflatoxin-safe maize produced by farmers in Nigeria is kept for their consumption. Other portion enters local and premium markets. Large quantities of aflatoxin-safe maize and groundnut have been produced—and continue to be produced—in other countries (Schreurs et al., 2019). This contributes to availability of safer and nutritious foods for farmers and the consumers purchasing crops/products in markets commercializing aflatoxin-reduced crops.

1.13. Double agricultural productivity and income of smallholder farmers (including women) through productive resources, inputs, knowledge

Good agricultural practices, correct input usage, biocontrol, and pre- and post-harvest technologies are promoted to increase both crop quality and productivity (Bandyopadhyay et al., 2019a). This management system allows maintaining high crop quality from field to fork. The production of aflatoxin-safe crops allows both female and male farmers to obtain higher income when selling crops to aflatoxin-conscious buyers (Narayan et al., 2019).

1.14. Access to markets

Integrated aflatoxin management increases farmers' chances to meet the stringent standards of local and international premium markets (Bandyopadhyay et al., 2019a). Poultry industries, processing companies, traders, among others, pay higher prices for aflatoxin-safe crops. In Nigeria, agro-enterprises can commercialize safe crops produced by smallholder farmers in premium markets and both agro-enterprises and farmers obtain higher income (Narayan et al., 2019). Another successful story is the re-launch of the long-time lost groundnut export sector in The Gambia.[5]

1.15. Opportunities for value addition

Little to no aflatoxin accumulates in crops produced with integrated aflatoxin management compared to crops managed using traditional practices. Higher quality crops can be sold at higher prices, for example to industries that seek aflatoxin-compliant crops producing ready-to-use therapeutic foods (RUTF) and complementary nutritious foods. See Target 2.5.

1.16. Sustainable food production systems

Integrated aflatoxin management allows producing crops with improved quality and in higher quantities. Greater, safer crop production occurs when farmers employ recommended pre- and post-harvest management practices. See Targets 2.5, 2.6.

1.17. Implementation of resilient agricultural practices to increase crop productivity

The Aflasafe Initiative promotes packages of technologies that enhance crop productivity, maintain high crop quality, and decrease pre- and post-harvest losses. See Target 2.3.

1.18. Access to fair and equitable sharing of benefits arising from the utilization of genetic resources

Biocontrol products are made available at scale in several SSA countries through manufacturing and distribution agreements. Farmers have access to beneficial fungal germplasm composing the products (i.e., the atoxigenic isolates). Biocontrol allows farmers to protect the crops they produce, consume, and commercialize. Research and commercialization strategies of the Aflasafe Initiative follow the objectives of the Convention on Biological Diversity: Conservation of biological diversity, Sustainable use of that diversity, and Fair and equitable sharing of the benefits arising out of the utilization of genetic resources. The atoxigenic isolates used in biocontrol products are fungal germplasm property of each country and thus all farmers have access to them in a fair manner.

1.19. Through international cooperation invest in infrastructure, agricultural research and extension, and technology development to enhance agricultural productivity

The Aflasafe Initiative coordinates substantial international cooperation efforts to develop biocontrol products, test pre- and post-harvest technologies, and design product manufacturing infrastructure (Bandyopadhyay et al., 2016, 2019b; Schreurs et al., 2019). All aflatoxin management projects are conducted with the aid of agricultural research and extension programs in participating countries. The capacity of extensionists, farmers, students, researchers, regulators, among other stakeholders to produce more, safer crops.

1.20. Prevent trade restrictions

When integrated aflatoxin management is used, crops significantly accumulate less aflatoxins, and most of those crops meet aflatoxin levels demanded by domestic and international aflatoxin-conscious markets. See Targets 2.5, 2.6.

1.21. Reduce premature mortality from non-communicable diseases

Consumption of aflatoxin contaminated crops can cause non-communicable diseases (e.g., cancer, immunosuppression) that may result in premature death (JECFA, 2018). Protecting crops from aflatoxins with integrated management allows producing healthy food and thus premature mortality can be reduced. See Targets 2.1, 2.2, 2.3.

1.22. Reduce deaths and illnesses caused by hazardous chemicals

Several diseases, and subsequent death, may be associated or caused by aflatoxin exposure. Rapid death has occurred in Kenya in 2004, 2005, 2010, and in Tanzania in 2016 and 2017 (Probst et al., 2012; Kamala et al., 2018). Use of holistic aflatoxin management allows reducing aflatoxin content and thus deaths and illnesses linked to aflatoxin exposure can considerably decrease. See Targets 2.1, 2.2, 2.3.

1.23. Strengthen the capacity to reduce and manage health risks

Crops protected with integrated aflatoxin management contain >80% less aflatoxins, sometimes 100% less, than non-protected crops. The capacity of farmers to use technologies that reduces aflatoxin prevalence and exposure is enhanced. There is an indirect reduction and management of health risks as a result of protecting crops from aflatoxins.

[5] Ramsay, D. 2019. Private sector development and international trade in The Gambia. Rural 21, International Journal for Rural Development. https://trade4devnews.enhancedif.org/en/impact-story/detoxifying-crops-gambia-ground.

1.24. *Access to quality early child development for all girls and boys to prepare them for primary education*

When aflatoxin-safe crops are available to prepare foods for pregnant and lactating mothers, exposure of children to aflatoxins significantly decreases. Once children are on weaning, baby food, and then on regular food, health risks are considerably reduced if those foods are prepared with aflatoxin-safe crops. Reduction of malnutrition, underdevelopment, and immunosuppression through consumption of aflatoxin-reduced crops contribute to quality child development and helps to prepare them for primary education. See Targets 2.1, 2.2, 2.3.

1.25. *Increase skills of youth and adults for decent jobs and entrepreneurship*

Through the Aflasafe Initiative, training on i) the contamination process, ii) aflatoxin mitigation strategies, iii) use of biocontrol, and iv) biocontrol manufacturing has been given to farmers, students, stakeholders, extensionists, private companies, among others. Also, jobs have been created as trainers on aflatoxin management as more enterprises begin to work with farmers to produce aflatoxin-compliant grains. In addition, manufacturers and distributors of Aflasafe are creating new jobs for people to work on the manufacturing and sale of the product. This has equipped both youth and adults with sets of skills to obtain and create jobs related to production of aflatoxin-safe crops.

1.26. *Scholarships for enrollment in higher education in technical/engineering/scientific programs*

Substantial research activities to develop biocontrol products and use of integrated aflatoxin management have been conducted by graduate students within Africa [University of Ibadan (Nigeria), Federal University of Agriculture – Abeokuta (Nigeria), University of Nairobi (Kenya), Kwame Nkrumah University of Science and Technology (Ghana)], the US (University of Arizona), and Germany (University of Bonn). More biocontrol products will be/are being developed along with students enrolled in universities in different countries.

1.27. *Give women equal rights to access natural resources*

Once an aflatoxin biocontrol product is commercially available, female and male farmers have equal rights to access the beneficial fungal germplasm composing products. There is no restriction of whom can buy and treat their crops with biocontrol. See Targets 2.4, 2.9.

1.28. *Enhance the use of enabling technology to promote the empowerment of women*

Women farmers using integrated aflatoxin management have obtained higher income. For example, in Nigeria, over 9500 women farmers have used the product and over 95% of their crops contained safe aflatoxin content, which industries paid a premium for. In addition, availability of aflatoxin-safe crops allows women to prepare safe and nutritious foods. Reduced aflatoxin exposure results in better health for them and their families and less resources and efforts are placed to take care for themselves and/or family members that could have been exposed to unsafe aflatoxin levels. See Targets 2.4, 2.9.

1.29. *Increase economic productivity through technological upgrading and innovation focusing on high-value products*

Farmers using integrated aflatoxin management have higher chances to produce crops meeting standards of aflatoxin-conscious buyers. If standards are met, crops can be sold at higher prices for preparation of diverse products (e.g., offered to industries that produce high-quality RUTFs, weaning foods, and breakfast cereals) and thus farmers' income increases. See Targets 2.6, 2.8, 2.10, 2.11.

1.30. *Promotion of development-oriented policies supporting productive activities, decent job creation, entrepreneurship, innovation, and encourage formalization and growth of micro-, small- and medium-sized enterprises*

In Nigeria, the Aflasafe Initiative worked with agro-enterprises (24 during 2018/2019 cropping season) that recruited, organized, and trained smallholder farmers to produce aflatoxin-safe maize. Some enterprises worked with <50 farmers while others worked with >10,000 (Narayan et al., 2019; Shenge et al., 2019). At harvest, the enterprises purchased at a premium a portion of the maize (60%–80%) and commercialized it in aflatoxin-conscious markets. This allowed establishing several micro- and small-sized enterprises and some grew to the medium-sized category. See Target 2.1. Similar efforts are underway in other countries. The establishment of biocontrol manufacturing facilities is promoting decent jobs, entrepreneurship, and diversification of established companies.

1.31. *Increase trade of high-quality crops in premium markets*

Crops protected with integrated aflatoxin management contain significantly less aflatoxin than non-protected crops and can meet tolerance thresholds that local, domestic, and international premium markets demand. Farmers producing aflatoxin-compliant crops can sell their crops at higher prices. See Targets 2.5, 2.11.

1.32. *Develop quality, reliable, sustainable and resilient infrastructure to support economic development and human well-being*

To industrially manufacture aflatoxin biocontrol products, the Aflasafe Initiative has developed technologies, processes, and infrastructure. In Ibadan, a manufacturing plant was constructed to supply products to Nigeria, Senegal, The Gambia, Burkina Faso, Ghana, Kenya, and Benin. Manufacturing facilities are now operating in Kenya, Senegal, and Tanzania. IITA-Tanzania manufactured products using a small-scale process for use in Tanzania, Malawi, Mozambique, Zambia, and Rwanda. More facilities are being constructed as additional products become registered and licensed. All manufacturing plants are of high quality and reliable for continuous and sustainable production and allow producing biocontrol products to grow aflatoxin-safe crops. This results in better health of farmers and consumers and higher income to farmers and crop-associated industries. In addition, the manufacturing plants provide decent job opportunities and generate profits to the investors.

1.33. Enhance scientific research

There are substantial scientific research efforts conducted during the development, registration, and commercialization of aflatoxin biocontrol products (Bandyopadhyay et al., 2016; Schreurs et al., 2019; Moral et al., 2020). These include studies on aflatoxin prevalence, fungal, testing candidate biocontrol agents, manufacturing biocontrol products, product formulation refinement, social science analyses, post-harvest technologies, market analyses, human exposure, poultry performance, among others. The Aflasafe Initiative has set up laboratories in Burkina Faso, Nigeria, Kenya, Mozambique, Malawi, Zambia, and is setting up labs in Sudan, Mali, DR Congo, and Burundi. This has enhanced research capabilities and training grounds for students and staff from various countries. The Aflasafe Initiative has enhanced scientific research and development in 22 SSA countries and provides technical assistance to aflatoxin management programs of Pakistan and Mexico.

1.34. Upgrade the technological capabilities of industrial sectors

Once an aflatoxin biocontrol product is registered for use within a country, the Aflasafe Initiative evaluates and selects the most appropriate companies to license manufacturing and/or commercialization to private companies or the public sector (i.e., in Kenya). Both manufacturing and quality control processes are transferred to the licensee. Also, aflatoxin testing support is provided to manufacturers and distributors, and interested agricultural enterprises for them to conduct the testing on their own. This results in an improvement of the capabilities of industries investing on biocontrol. See Target 9.1.

1.35. Encourage innovation and public and private research and development

Research and development efforts have been possible by obtaining grants from both public and private sector organizations. Innovative processes to increase efficiency and versatility of biocontrol manufacturing and field performance have been developed (Ortega-Beltran et al., 2021a).

1.36. Support domestic technology development, research, and innovation by ensuring a conducive policy environment, industrial diversification, and value addition to commodities

Aflatoxin biocontrol products are developed along with local national institutions and partners. Regulatory agencies and policy makers are consulted and sensitized before a project start. Their advice is incorporated into the research. Those institutions/partners recognize that biocontrol will benefit populations. Participating countries receive advise to i) improve their capacity to monitor, regulate, and control, ii) develop aflatoxin standards based on dietary habits, and iii) reinforce food safety risks assessment, inspection, and analysis systems. See Target 1.5. Manufacturing biocontrol is helping to diversify economies by producing the only practical solution to decrease crop aflatoxin content from field to plate. Use of integrated aflatoxin management results in added value to the high-quality crops produced.

1.37. Increase income of smallholder farmers

See Targets 8.1, 8.2, 8.3.

1.38. Increase official development assistance and financial flows, including foreign investment to countries in accordance with their national agricultural plans and programs

See Targets 1.4, 2.10, 9.4. In all cases, activities are bridged to the needs of countries' agricultural agendas. Biocontrol is an important aflatoxin mitigation tool in the national agricultural investment plans of Nigeria, Tanzania, Senegal, The Gambia, Malawi, and Uganda.

1.39. Support positive economic, social and environmental links between urban, peri-urban and rural areas

Treatment of crops with biocontrol and production of aflatoxin-safe crops occurs in peri-urban and rural areas. A portion of aflatoxin-safe crops is sold in informal markets of urban areas. Other portion enters the formal sector and the transformed products reach urban areas. Urban populations benefit from aflatoxin management strategies in peri-urban and rural areas.

1.40. Sustainable management and efficient use of natural resources

See Target 2.9.

1.41. Reduction of food waste at retail and consumer levels

Overall, practices of integrated aflatoxin management contribute to reduce food waste by minimizing rejection of grain lots due to aflatoxin content higher than permissible levels. Crops become protected until consumption, and this helps reducing food waste.

1.42. Reduce food losses along production and supply chains, including post-harvest losses

Integrated aflatoxin management reducing aflatoxin contamination, crop rot and rejects while sorting at both pre- and post-harvest stages. See Target 12.2.

1.43. Achieve environmentally sound management of chemicals and reduce their release to minimize impacts on human health

Integrated aflatoxin management prevents crop contamination with aflatoxins through use of practical, environmentally sound technologiesThis allows reducing aflatoxin exposure and associated health risks of these dangerous compounds. See Targets 1.3, 2.2, 3.1.

1.44. Strengthen scientific and technological capacity of developing countries to move towards more sustainable patterns of consumption and production

Graduate students significantly contribute to the development of aflatoxin control technologies for use in their countries. In many cases, the students implement lessons learned and developed during their studies and continue contributing towards aflatoxin mitigation in distinct countries, after completing their studies. Researchers of national institutions also receive training. This contributes to improved, sustainable productive systems. See Target 9.5.

1.45. Strengthen resilience and adaptive capacity to climate-related hazards

See Target 1.2.

1.46. Improve education, awareness-raising and human and institutional capacity on climate change impact reduction

Across several countries, substantial efforts have been made to sensitize farmers, their families, key stakeholders, regulators, and consumers, on the dangers of aflatoxins, their impact, the exacerbation of the problem by climate-change, and how integrated aflatoxin management can decrease crop contamination.

1.47. Promote mechanisms for raising capacity for effective climate change-related planning and management

Capacity of famers and key stakeholders to reduce impacts of the contamination process, including when experiencing conditions associated with climate change, is increased through training sessions in the different participating countries.

1.48. Ensure the conservation and sustainable use of terrestrial ecosystems and their services, in line with international agreements

See Targets 1.1, 2.9.

1.48.1. Promote fair and equitable sharing of benefits arising from the utilization of genetic resources and promote appropriate access to such resources, as internationally agreed

See Target 2.9.

1.49. Mobilize and significantly increase financial resources from all sources to conserve and sustainably use biodiversity and ecosystems

See Targets 1.4, 2.10, 9.4. In all cases, activities consider the conservation and responsible use of fungal germplasm composing a biocontrol product.

1.50. Mobilize financial resources from multiple sources

See Targets 1.4, 2.10, 9.4. To capitalize efforts at scale the Aflasafe Initiative jointly advocates and mobilizes resources with government agencies, donors, private sector, and NGOs. The private sector Aflasafe manufacturers and distributors and actors in the value chain have invested considerably in aflatoxin management. The governments in several countries are providing subsidies and innovative financing mechanisms to incentivize use of Aflasafe and other aflatoxin management practices.

1.51. Enhance North-South, South-South and triangular regional and international cooperation on access to science, technology and innovation and enhance knowledge sharing on mutually agreed terms

The Aflasafe Initiative collaborates at national, regional, and international levels, with diverse donors, governments, universities, research institutions, NGOs, development agencies. Examples include i) North-South cooperation between USDA-ARS and IITA in which the former provided royalty-free access to the biocontrol technology; ii) South-South scientific, technological and innovation cooperation by IITA and multiple national agricultural research partners; iii) South-South knowledge sharing cooperation by IITA and several partners in Pakistan; iv) triangular international cooperation among multiple institutions in EAC (universities, NARS, regulatory bodies, grain producers and trading bodies associations, private sector), IITA, and USDA-ARS collaboration on scientific, technological, innovation, and knowledge sharing. In all cases, the collaboration and/or cooperation terms are specified prior to commencement of any project and the activities always adhere to those terms.

1.52. Promote the development, transfer, dissemination, and diffusion of environmentally sound technologies

See Targets 1.1, 9.3.

1.53. Fully operationalize the technology bank and science, technology and innovation capacity-building mechanism

See Targets 9.1, 9.2, 9.4.

1.54. Enhance the use of enabling technology

Having a biocontrol product available nationwide, and converging it with other management practices, allows farmers to produce aflatoxin-compliant crops. Farmers then can commercialize their crops at higher prices than non-treated crops.

1.55. Enhance international support for implementing effective and targeted capacity-building to support national plans to implement all SDGs

See Targets 1.4, 2.10, 17.2.

1.56. Significantly increase exports

See Targets 2.5, 2.11, 8.3.

1.57. Enhance partnerships for sustainable development, complemented by multi-stakeholder partnerships that mobilize and share knowledge, expertise, technology and financial resources, to support the achievement SDGs

See Targets 2.10, 17.2.

1.58. Encourage and promote effective public, public-private and civil society partnerships, building on the experience and resourcing strategies of partnerships

Use of integrated aflatoxin management at scale has been possible through partnerships with government and private entities interested in manufacturing and distributing biocontrol products, and interested in producing aflatoxin-compliant crops. For this, involvement of farmers and farmers' organizations is critical. The Aflasafe Initiative encourages and promotes coordinated actions among farmers, governments, development partners, researchers, agricultural organizations, policy makers, health-sector, and other relevant stakeholders to achieve improved food safety and lower food security risks.

2. Potential contributions to other SDGs

Two SDGs are out of the scope of the Aflasafe Initiative: Number 6, **Clean Water and Sanitation**, and Number 7, **Affordable and Clean Energy**. Potential contributions to the remaining SDGs, 14 and 16, are briefly described below.

Use of aflatoxin-safe crops to manufacture feeds for shrimps, fish, oysters would result in increased productivity, reduced mortality, higher income for producers, and availability of aflatoxin-safe products to consumers.

Both increased income as a result of producing safer, more valuable crops and the possibility of creating decent job opportunities can contribute to reduce problems associated with violence, conflicts, and migration (abuse, trafficking, exploitation).

3. Conclusions

In Africa, millions of smallholder farmers and therefore millions of consumers pay a large health, economic, and development toll by the lack of practical, accessible, and effective aflatoxin mitigation tools. Fortunately, biocontrol coupled with other management strategies offers a practical solution and is getting traction in several countries. To date, 14 Aflasafe products have been registered for use in 10 countries and more are being developed and tested. A cascade of positive outcomes, many contributing to achieve the SDGs, is expected in countries where biocontrol is available for use at scale.

Certainly, achieving each SDG is a complex, tremendous task for each country. However, it is the sum of diverse, multiple approaches by diverse actors what will make possible achieving each SDG. Tailored agro-food and small-scale poultry systems can make important contributions towards achieving the SDGs (Wong et al., 2017; Tanumihardjo et al., 2019). Similarly, integrated aflatoxin management can contribute, at different scales, to improve health, economic, social, and development sectors and this can help to fulfill several objectives of most SDGs. On the other hand, successful aflatoxin control has its own complexities. All responsible actors must work in a collective, concerted manner to converge available technologies to mitigate aflatoxins. The Aflasafe Initiative promotes appropriate aflatoxin management strategies designed by considering knowledge from diverse disciplines, many of them unconventional for traditional agricultural systems. There is no doctrinaire approach in the design of the strategies; the context is different across and within countries and the strategies must be tailor-made to be effective.

More than 150,000 farmers have used integrated aflatoxin management in nearly 1 million acres of maize and groundnut in Nigeria, Kenya, Senegal, The Gambia, Burkina Faso, Ghana, Tanzania, Malawi, and Mozambique. Large-scale use of integrated aflatoxin management is poised to improve domestic food safety, reduce aflatoxin exposure, and increase compliance with international food safety trade standards. However, although significant progress has been made to solve a highly complex problem, considerably more efforts are needed to promote large-scale use of aflatoxin management programs in countries where these practices are currently used in target crops and other susceptible crops, and similar programs need to start in countries where aflatoxin contamination is prevalent. In addition, there are several other mycotoxins that contaminate crops in SSA, that may co-occur along with aflatoxins (JECFA 2018). Some of the technologies composing the strategies designed by the Aflasafe Initiative (e.g., insect control, drying, appropriate storage) may also be effective to reduce accumulation of mycotoxins other than aflatoxins. Other solutions such as cultivars resistant to target mycotoxins could be incorporated in agronomic packages to reduce incidences of other mycotoxins that may co-occur along with aflatoxins in susceptible crops (Ortega-Beltran et al., 2021b).

Finally, research and development programs related to agriculture should promote economic growth, market diversification, gender equality, food security and safety, creation of decent jobs, and tackle climate change. The Aflasafe Initiative is a progressive CGIAR program that addresses those needs and therefore can have major impacts towards achieving several targets of most SDGs. Only with broad, comprehensive strategies a technology will be able to contribute to achieve one or various of the SDGs.

Author's contributions

A.O.-B. and R.B. conceptualized the idea. A.O.-B. drafted the original manuscript. A.O.-B. and R.B. finalized the manuscript.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The authors receive no direct financial benefit from the manufacturing and marketing of any of the aflatoxin biocontrol products mentioned in this article. The Aflasafe name is a Trademark of the International Institute of Tropical Agriculture (IITA). IITA used to manufacture and commercialize Aflasafe for use in Nigeria, Senegal, Burkina Faso, The Gambia, and Ghana. Manufacturing and distribution responsibilities have been licensed to the private or public sector. IITA charges a small licensing fee to manufacturers for use of the Aflasafe name and cost associated with technology transfer and technical backstopping. This fee is reinvested for providing reasonable technical support to the manufacturers and distributors when needed, to develop new products/practices for more farmers to use the technology, as well as for further aflatoxin research to improve the biocontrol technology. A portion of the fee is also set aside for fulfilling reasonable Access and Benefit Sharing obligations related to the Convention on Biodiversity. Both authors are employed by IITA.

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