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RESEARCH ARTICLE

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Bridging the gap? Public–private partnerships and genetically modified crop development for smallholder farmers in Africa

Brian Dowd-Uribe[1,2,3] | Joeva Sean Rock[4] | Trevor Spreadbury[5] | Patricia Chiril[5] | David Uminsky[5]

[1]Department of International Studies, University of San Francisco, San Francisco, California, USA

[2]UMR Innovation, Montpellier, France

[3]Montpellier Advanced Knowledge Institute on Transitions, Université de Montpellier, Montpellier, France

[4]Department of Politics and International Studies, University of Cambridge, Cambridge, UK

[5]Data Science Institute, University of Chicago, Chicago, Illinois, USA

Correspondence
Joeva Sean Rock, Department of Politics and International Studies, University of Cambridge, Cambridge, UK.
Email: jr872@cam.ac.uk

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Societal Impact Statement

Genetically modified (GM) crops have the potential to address multiple challenges for African smallholder farmers but are limited by several institutional constraints. Public–private partnerships (PPPs) are seen as an organizational fix to one such constraint, bringing privately held intellectual property rights on key crop technologies to African public institutions to develop GM crops for smallholder farmers. Here, a new comprehensive dataset of GM crops in Africa is used to understand the extent and efficacy of PPP-led GM crop development for smallholder farmers and discuss what might limit their potential in the future.

Summary

- Genetically modified (GM) crops are promoted as a key tool to address multiple challenges in Africa, including the impacts of climate change and food insecurity. Observers have noted, however, significant institutional challenges to achieving such goals, most notably, intellectual property rights (IPR) to key GM traits being held by private companies who have limited incentives to develop those technologies for smallholder farmers. To bridge the gap between privately held IPR and pro-poor crop breeding, advocates have called for increased funding for institutional innovations such as public–private partnerships (PPPs) to facilitate the transfer of crop technologies from private companies to public research institutes.
- For the past two decades, donors and firms have invested considerable resources toward PPPs. However, to date, few research efforts have empirically examined the extent and effectiveness of PPPs at the continental scale.
- This study draws from a new comprehensive dataset on GM crop research and development in Africa to examine whether the anticipated advantages of PPPs have resulted in an improved ability to deliver GM crops to smallholder farmers.
- We find that although PPP research has focused on crops and traits more relevant for smallholder farmers, many of these efforts have been suspended, with only one crop thus far reaching the hands of farmers. PPPs can address some issues related to GM crop development but still appear constrained by other institutional

challenges, which may limit their development, reach, and the achievement of targeted benefits for smallholder farmers.

KEYWORDS
Africa, agricultural research for development, genetically modified crops, new breeding technologies, public–private partnerships

1 | INTRODUCTION

A key question dominating early debates over genetically modified (GM) crops was whether they could benefit smallholder farmers, particularly in Africa. GM crops first became commercially available in the mid-1990s but were originally concentrated almost exclusively in the United States (James, 2000). Those GM crops that did make it to the Global South in the early 2000s were principally directed toward large-scale commercial growers of commodity crops, first in Argentina, and later in Brazil. Though many suggested that GM crops could serve Africa's small farmers, very little research was originally being directed to those aims (Qaim, 1999). Private companies saw little incentive to create GM crops for small and poor farmers (Elliot & Maden, 2016; Lipton, 2007), particularly in Africa, where weak intellectual property rights (IPR) protections, small formal seed markets, and high levels of seed saving predominated (Herdt, 1995). Significant challenges existed for public research institutes to fill this gap (Pingali & Raney, 2005; Spielman & Zambrano, 2013). Private companies held the IPR to important traits making it difficult for public institutions to conduct their own GM crop research (Cohen, 2001). Notwithstanding issues with IPR, African public research institutes were chronically underfunded and lacked the infrastructure and investment to conduct GM crop research (Omotesho & Falola, 2014; Roseboom & Flaherty, 2016).

One proposal to address the challenges faced by purely public or private research was to shift attention toward building cooperation between private and public entities to achieve GM crop gains for Africa's smallholder farmers (Chataway, 2005; Cohen, 2001; Pray, 2001). Most commonly referred to as public–private partnerships (PPPs), this cooperation for the development of GM crops can take many forms, from joint research endeavors, to the transfer of traits, to the licensing of particular technologies, among others (Byerlee & Fischer, 2002; Spielman & Grebmer, 2006).

Over the past three decades, there has been considerable effort and resources dedicated to creating PPPs with the goal of developing GM crop technologies appropriate for poor smallholder farmers in Africa. The first significant PPP began in the mid-1990s between Monsanto and the Kenya Agricultural Research Institute to breed a GM disease-resistant sweet potato. To assist in developing similar partnerships, intermediary organizations, first the International Service for the Acquisition of Agri-biotech Applications (ISAAA), and then the African Agricultural Technology Fund (AATF), were founded (Boadi & Bokanga, 2007; James, 1997; Schurman, 2017). Since then, several PPPs have been formed to create GM crop varieties designed specifically for African smallholder farmers, a trend that appears to be continuing with the use of gene editing for crop development (Rock et al., 2023; Schnurr, 2019).

A small but growing literature has begun to examine GM crop PPPs raising important insights and questions. While some contend that PPPs allow for public and private institutions to exchange expertise and build innovations responsive to farmer-needs (Boadi & Bokanga, 2007; Spielman & Zambrano, 2013), others argue that PPPs are overly complex (Rock & Schurman, 2020) and limited by competing incentives and goals (Pingali & Raney, 2005). Others point to the challenge of developing GM crop technologies for a highly heterogeneous smallholder farming population (Dowd-Uribe, 2017), with vastly different levels of capitalization, access to land, labor and seeds, household size and composition, and livelihood strategies, among others (Chikowo et al., 2014; Tittonell et al., 2010).

Despite substantial material support and promise of success, the limited available research is insufficient to understand multiple dimensions of GM crop PPPs in Africa at scale. Current research is spread across a limited number of case studies, many of which do not explicitly connect findings to the organizational arrangements driving research and development efforts. This makes it difficult to understand the full breadth of GM crop PPPs, and how they perform comparatively across a number of metrics. Importantly, it remains unclear whether the anticipated advantages of PPPs have resulted in an improved ability to deliver GM crops to poor smallholder farmers.

The research presented in this paper draws from a new GM crop database constructed by the co-authors to offer reflections and analysis on these research gaps. First, we review the literature on PPPs and GM crop development with a specific focus on Africa. We then describe the state of GM crops in Africa by characterizing the development of particular GM crop varieties in one of four organizational categories: (a) private, (b) public-private tech fee, (c) public-private, and (d) public. Next, we use our results to help to answer the key tensions noted above. Finally, we conclude with a discussion of the relevance of these findings for GM crop research and development for small farmers in Africa.

1.1 | PPPs and GM crop development in Africa—a review

Since the growth of the agricultural biotechnology industry, thanks in part to changes in patenting rights and the continual underfunding of public research organizations, the literature has been finely attuned to both the organizational and institutional elements of the technology, and how they interact to produce certain outcomes. Here, *organization* refers to "bodies such as enterprises, research institutes, farmer cooperatives, and government or non-governmental organizations" and *institution* to "sets of common habits, routines, practices, rules or laws that regulate the relationship and interactions between individuals and groups" (Hall, 2005: 615).

Organizationally, the literature has asked *who* is best equipped to advance the technology for smallholders in the Global South. Early on, many argued for public-driven research, contending that "biotechnologies should be used to maintain local expertise and germplasm" in order to develop locally-relevant crops and technologies, and bolster public sector research (IAASTD, 2009: 15; Juma, 1989). However, the introduction of IPR altered the plant breeding sphere completely: "The break between public and private sector plant improvement efforts came with the advent of biotechnology, especially genetic engineering. The proprietary protection provided for artificially constructed genes and for genetically modified plants provided the incentives for private sector entry" (Pingali & Raney, 2005: 4).

IPR are just one of many key institutional elements—and tensions—the literature has been organized around. These include an attention to IPR held by firms and how to persuade patent holders (firms) to develop crops relevant for smallholder farmers; the various research and development (R&D) capacities and expertises of public organizations; research partnerships and how to best organize them to maximize outcomes; regulatory regimes and associated costs; the geographic dimensions of these research endeavors, including where research, field trials, and commercialization take place; and the institutional dimensions facilitating the adoption and performance of GM crops, including seed systems and how GM crops may or may not fit into them, and the existence (or lack thereof) of available credit and agricultural extension support (Chataway, 2005; Pingali & Raney, 2005; Spielman & Zambrano, 2013).

Some have advanced *public–private partnerships* as an organizational solution to overcome some of these institutional hurdles (Chataway, 2005: 604; Pray, 2001). Early literature on GM crop PPPs with a focus on the African continent wrote from an anticipatory lens, tracing various pathways in which public and private organizations might work together (Tripp, 2002). Much of this literature focused on public sector organizations—African universities, research organizations, and seed companies—and to some extent, CGIAR centers,[1] to assess how best to balance differing capacities and goals of public organizations with those of private actors (Byerlee & Fischer, 2002). The overall assumption here was that African public organizations would be largely unable to drive their own agricultural biotechnology initiatives, given their limited resources and infrastructure (with the exception of South Africa), and hurdles posed by IPR. To that end, while some argued that PPPs could be mutually beneficial (Boadi & Bokanga, 2007; NASAC, 2015; Spielman & Zambrano, 2013), others were skeptical of the ability of public organizations to drive shared initiatives and derive benefits. Tripp (2002), for instance, was critical of the idea that including public organizations would necessarily result in "pro-poor" plant breeding projects: "public breeding programmes can be as protectionist as their private counterparts… [and] public research [is not] necessarily pro-poor" (2002: 241). Others, such as Pingali and Raney (2005), argued that PPPs would not be enough to encourage private firms to work on crops of importance to smallholder farmers.

Since these early debates, GM crop research and design has expanded across the continent, both through and outside of PPPs. As expectations around the technology's promise expanded, so have empirical studies assessing their design, outcomes, and interactions among project partners (Luna & Dowd-Uribe, 2020; Schnurr, 2019). For example, Dowd-Uribe's (2023) study on the pod borer resistant (PBR) cowpea in Burkina Faso, which contains a Bt (*bacillus thuringiensis*) gene to ward off one of its most pernicious pests—the leaf pod borer. This research highlights how GM crop varieties can be implicitly designed to target larger and more commercially-oriented farmers rather than the project's stated beneficiaries of women and poor smallholder farmers. Local contexts, whether in terms of crop varieties or state governance, matter in the shaping of agricultural biotechnology projects and outcomes. Writing on early PPPs between the Kenyan Agricultural Research Institute and various private partners, Harsh and Smith argued that a lack of legal instruments and guidelines around agricultural biotechnologies initially attracted, rather than deterred, biotech donors to Kenya (2007: 253). Others have assessed partnerships forged by AATF, a mediary organization established by the Rockefeller Foundation and several biotechnology firms in the early 2000s to facilitate PPPs between African organizations and firms (Boadi & Bokanga, 2007; Schurman, 2017).[2] Studies on AATF projects have highlighted the prioritization of the interests of firms and donors over their African counterparts (Rock, 2022; Schnurr et al., 2020), high coordination costs (Ezezika & Daar, 2012), and confusion among project participants regarding who owns outputs (Ignatova, 2015).

Taken as a sum, the literature on GM crop development in Africa, as it relates to PPPs, can largely be categorized into two main groupings. The first is composed of the theoretical debates of the early 2000s, where questions around efficacy, design, and probability were heavily debated. The second is that of more recent literature, which largely looks at individual GM crop projects and outcomes. There are two main gaps in this collective literature. First, to our knowledge, there have not yet been attempts to empirically answer the theoretical debates of the early 2000s, leaving key questions around whether PPPs could serve as an organizational solution to institutional hurdles largely unanswered. Second, the empirical work that has been done on individual GM projects and outcomes, while offering valuable insights into internal dynamics of GM crop research and production, has not necessarily engaged with the PPP literature, nor explicitly included organizational arrangements as a key variable of analysis. This is not a critique but rather an opportunity to explore GM crop PPPs at scale while also being attendant to internal project dynamics,

[1]There is disagreement within the literature over how to categorize the 14 research centers that fall under the CGIAR. Some consider them simply public organizations (Spielman & Zambrano, 2013), while others describe them as "international public sector" (Pingali and Raney, 2015). In our paper, we categorize them as "public," and geographically by the respective centers' headquarters.

[2]The AATF has received impressive support from development donors, namely USAID, BMGF, and DFID, and is seen as a leading initiative in bringing GM crops to African farmers (Dowd-Uribe et al., 2022).

organizational considerations, and project outcomes. Below, we seek to fill these gaps with a goal of better understanding if and how PPPs have been able to develop GM crops for poor smallholder farmers in Africa.

2 | MATERIALS AND METHODS

We characterize GM crop research and development in Africa by drawing from a unique dataset developed by the Mapping Biotechnologies in Africa, or mBio, Project. The authors are all members of the mBio Project and co-constructed this dataset with the assistance of a team of graduate research assistants. We describe the methods used to construct the database briefly; see Grzenda et al. (2022) for a more detailed explanation of the employed methods. The dataset is publicly available at www.mbioproject.org.

The mBio dataset draws from several data sources to construct the most comprehensive and up-to-date dataset of GM crop research and development in Africa. A key data source is the ISAAA, a non-profit organization funded principally by the biotech industry. The ISAAA operates a global GM Approval Database, which we scraped as a primary data source. This database is widely considered to be an industry goldstar for information pertaining to GM crops (Spielman & Zambrano, 2013). Nonetheless, the ISAAA database has some important limitations, particularly when the goal is to characterize the full extent of GM crop research and development in Africa. One such shortcoming is the lack of information after a GM crop achieves an approval. A GM crop may be approved but never commercialized, or commercialized but then later suspended. Moreover, the ISAAA database does not provide information on the organizational dimensions of GM crop development, nor does it contain information on those crops that are in the research pipeline, but which may not have reached the approval stage.

We attempted to address some of these shortcomings, and supplement further information, by conducting a thorough review of the available literature. This review included noteworthy reports published by the United States Department of Agriculture and the ISAAA. The review also included, where relevant, GM crop project reports, peer-reviewed literature, donor websites, news sources, and other gray literature. These data were then synthesized with the ISAAA data to create a unique searchable dataset organized by individual GM crop varieties.

GM crop varieties refer to a crop variety with a unique GM trait or set of traits. Unique GM traits are determined via the identification of the specific functional genes inserted in the transgenesis process. These functional genes are reported in the ISAAA dataset, and, in some cases, supplemented via other sources. Often, there are multiple unique GM crop varieties that have the same traits but different functional genes. For example, our database contains multiple herbicide tolerant GM maize varieties. We differentiate unique GM herbicide tolerant maize varieties based on the functional genes used in their transformation. In some cases, the same unique GM crop variety may be developed in different countries or under different organizational groupings (see below). In the few cases where our database contains information on multiple parent varieties for a GM crop variety with a unique GM trait or set of GM traits, we classified these as only one unique GM crop variety.[3] In some figures, we categorized crops by crop types (e.g., fruit and nuts, cereals); Methods S1 contains more information.

These GM crop varieties were then sorted into organizational groupings. This sorting was achieved by an examination of the developers—institutions contributing to GM crop research and development—of each of the GM crop varieties. The developers of a particular GM crop were found via an examination of GM crop project reports and other relevant literature. Each of the developers was then categorized as public or private. For the purposes of this research, private refers to for-profit companies and industry-funded research institutes. Public refers to not-for-profit institutions, the vast majority of which are public research institutes and public universities. Three government-run parastatals and institutions from the CGIAR system were classified as public. In total, we identified 89 developers including: 47 developers based in Africa (public = 41, private = 6), 34 developers based outside of Africa (public = 15, private = 19), and 8 developers that belong to the CGIAR system.

GM crop varieties that were produced solely by private institutions were placed into the category *private*. GM crop varieties that were produced by a private company in conjunction with other public institution(s) were placed into one of two categories: *public–private partnership technology fee* (herein referred to as the *PPP tech fee group*) or *public–private partnership* (herein referred to as the *PPP group*). The distinction between these two categories is the presence of a technology fee associated with the sale of the GM crop variety to farmers. Those in the PPP group have publicly stated that there will be no technology fee associated with the sale of GM crop varieties to farmers.[4] In these cases, some form of licensing arrangement was arrived at between the patent holder, most often a private company, and the public institutions developing the technology for African farmers. The last category, *public*, contains those GM crop varieties that are developed exclusively by public institutions, including the CGIAR.[5]

Each GM crop variety was classified into one of four categories that characterize the extent of research and development activities: (1) *Under Development*: refers to a GM crop variety in an any stage of development—usually in a laboratory setting—prior to field trials; (2) *Research Trials*: refers to a GM crop variety being tested in field conditions; (3) *Approved*: refers to a GM crop variety that has been approved for commercialization by regulatory authorities, but is not yet available for commercial purchase and/or use; (4) *Commercialized*: refers to a GM crop variety is available for commercial purchase and/or use.

[3]To illustrate this point, our database contains three parent varieties for the pod borer resistant (PBR) cowpea. We only classify this as one GM crop variety given that (a) data on parent varieties is incomplete and difficult to obtain across our dataset, and (b) details at the parent variety level are often excluded from discussions on GM crop research and development.

[4]One exception is WEMA maize. Project reports state that it will be sold without a technology fee to small farmers. Large-scale commercial farmers in South Africa, however, will pay a technology fee (African Centre for Biodiversity, 2017). Nonetheless, we categorized WEMA maize in the PPP group.

[5]It is possible that some GM crop varieties that are currently categorized as public had some partnerships or licensing agreements with private entities, but those linkages are unknown. This may mean that the total number of public GM crop varieties is overstated.

Each GM crop variety was also classified in terms of research status: (1) *Active*: where evidence was found that development and/or commercialization of the GM crop is ongoing; (2) *Suspended*: where evidence was found that development and/or commercialization of the GM crop has been discontinued; (3) *Unknown*: where there is insufficient data available to determine status.

This research uses two counting frameworks depending on the type of analysis. For those instances where unique crop varieties and/or traits are the unit of analysis, we count unique GM crop varieties only once, even if that same variety is present in multiple countries. This is the convention used in Figures 2 and 3. For those instances where the analysis is geographic in nature, and/or where the development stage or research status are the unit of analysis, we count GM crop varieties by country. In other words, we count each instance that a unique GM crop variety is present in a different country. This is the convention in Figures 1, 4, and 5. Other minor alterations to these conventions are mentioned in figure titles, where relevant.

3 | RESULTS

The mBio dataset allows for deeper insight into the extent, focus, and research stage of GM crop research as it relates to organizational configuration. In terms of overall GM crop research, the dataset identifies 172 crop varieties[6] that have been or are currently being developed across 19 countries[7] (see Figure 1). The top five countries with the most entries were South Africa, Nigeria, Egypt, Uganda, and Kenya; together, 82% of crop varieties are found in these countries. Overall, 52.9% of GM crop varieties in the dataset were developed by private entities, 7.6% by PPP tech fee, 8.7% by PPP, and 26.7% by public entities. Each organizational group is discussed below.

The private group has developed or is developing 91 GM crop varieties. The vast majority of these crops are found in two African countries, with 74.7% found in South Africa and 27.5% found in Nigeria. Multinational seed companies, including Bayer CropScience,[8] BASF, Syngenta/ChemChina, and DuPont/Pioneer (Corteva), develop 90% of these crops. Almost all of the remaining, or six GM crop varieties, are developed by private sugarcane research institutions in South Africa and Mauritius.

The PPP tech fee group comprises partnerships between a technology holder and a public institution in Africa where farmers will be charged a technology fee for the proprietary technology in the GM crop variety. Partnerships in this group have developed, or are developing, 13 GM crop varieties across nine African countries. The vast majority, or 10, of these partnerships are between the multinational seed company Bayer CropScience and an African parastatal or research institute. The most widely recognized of this group is the public–private partnership that brought insect resistant Bt cotton to smallholder farmers in Burkina Faso from 2008 to 2016 (Dowd-Uribe & Schnurr, 2016).

The PPP group comprises 11 total projects made up of five multi-country projects and six individual country projects. The five multi-country projects are the Water Efficient Maize for Africa (WEMA) program (Ethiopia, Kenya, Mozambique, Nigeria, South Africa, Tanzania, and Uganda), the African Biofortified Sorghum (ABS) project (Burkina Faso, Kenya, Nigeria, and South Africa), the Nitrogen Efficient Water Efficient Salt Tolerant (NEWEST) rice program (Nigeria, Ghana, and Uganda), the Virca Plus Cassava program (Kenya, Nigeria, and Uganda), and the PBR cowpea program (Burkina Faso, Ghana, Malawi, and Nigeria). These 11 projects are developing 15 unique GM crop varieties across a total of 11 African countries. In most cases, an intermediary organization, the AATF, negotiated a licensing agreement with a private partner for the use of their technology to produce a particular GM crop.

The public group comprises research conducted by partnerships or individual public institutions—primarily national research institutes and/or universities. In total, public entities have developed, or are developing, 46 unique GM crop varieties. Over half, or 22 in total, are concentrated in two countries, Egypt with 12 and South Africa with 12. At least 16 of these involve intercontinental partnerships, where an African-based research institution or university partners with a public research institution or university outside of Africa.

GM crop development differs across these four groups (see Figure 2). The vast majority of private GM crop development, or 88%, is focused on three main crops: maize, cotton, and soybean. More than a quarter, or 26.7% of all GM crop varieties, have been or are being developed exclusively by public institutions. Public research focuses on a larger suite of crops, including eight total crop categories and 21 total crop varieties. Less than a tenth, or 8.7% of all GM crop varieties, have been developed or are being developed by public–private partnerships. Similar to public institutions, PPPs have developed a diverse suite of crops from five different crop categories. PPP tech fee projects have developed or are developing only 13 total crop varieties, and, similar to the exclusively private research, it is focused exclusively on a small range of crops. All but one of the crops derived by a PPP tech fee partnership was a variety of maize or cotton.

Two traits dominate GM crop research and development in Africa, herbicide tolerance and insect resistance (see Figure 3). Together, one or both traits are present in 62.2% of GM crop varieties. The third most developed trait is disease resistance, present in 19.2% of GM crop varieties. Together, one of these three traits are found in 81.4% of all GM crop varieties.

The concentration of research on herbicide tolerance and insect resistance is particularly pronounced for those GM crop varieties developed by private companies. Herbicide tolerance is present in 75.8% of the GM crop varieties developed by private companies,

[6]This number only counts unique GM crop varieties. It does not double count the same unique GM crop variety when they appear in different countries. All country-specific mentions of GM crop varieties use the total number of instances where these crop varieties have been introduced into a specific country (i.e., 219), in order to give a more accurate representation of the geographic distribution of these crop varieties.

[7]The countries are: Burkina Faso, Cameroon, Egypt, Eswatini, Ethiopia, Ghana, Kenya, Malawi, Mauritius, Morocco, Mozambique, Nigeria, South Africa, Sudan, Tanzania, Tunisia, Uganda, Zambia, Zimbabwe.

[8]Many of these partnerships and programs were originally developed by Monsanto. Bayer CropScience acquired Monsanto in 2018. We refer to Bayer CropScience in this paper to reference those programs and projects begun by Monsanto and Bayer CropScience.

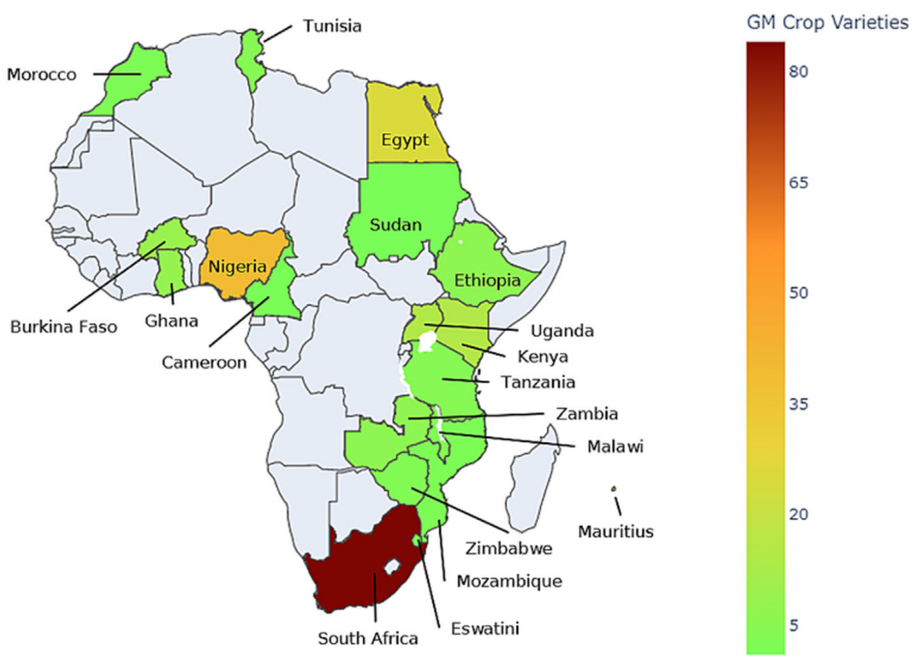

FIGURE 1 Number of genetically modified (GM) crop varieties that have been or continue to be developed in each African country. Gray denotes that there has never been GM crop research or development in that particular country.

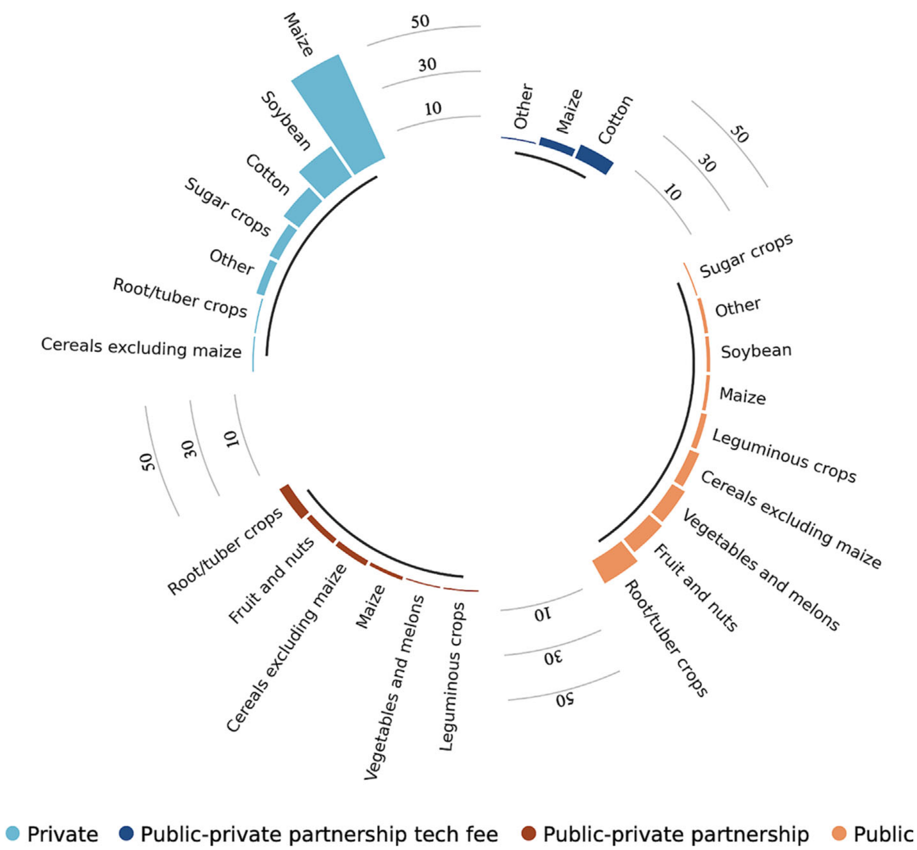

FIGURE 2 Genetically modified (GM) crop varieties categorized by organizational groups and broken down by crop category in Africa. In some rare cases, GM crop varieties may be counted more than once given their deployment in different countries under different organizational arrangements. Crop categories were modified slightly from the Food and Agriculture Organization of the United Nations' crop categorization definitions to match the dataset. See Methods S1 for the complete list of crops and how they were categorized.

insect resistance in 59.3%, and one of the two are present in 93.4%. Public research on GM crop development has been principally focused on disease resistance, comprising 52.2% of the total traits developed by these entities. PPPs trait development is more distributed, with disease resistance, insect resistance, drought tolerance and nitrogen use efficiency each occupying 46.7, 20.0, 13.3, and 13.3% of their research, respectively.

A minority of GM crop development in Africa—13.2%—has been commercialized (see Figure 4); of that, almost all the GM crop varieties to reach the hands of the farmers have been developed solely by

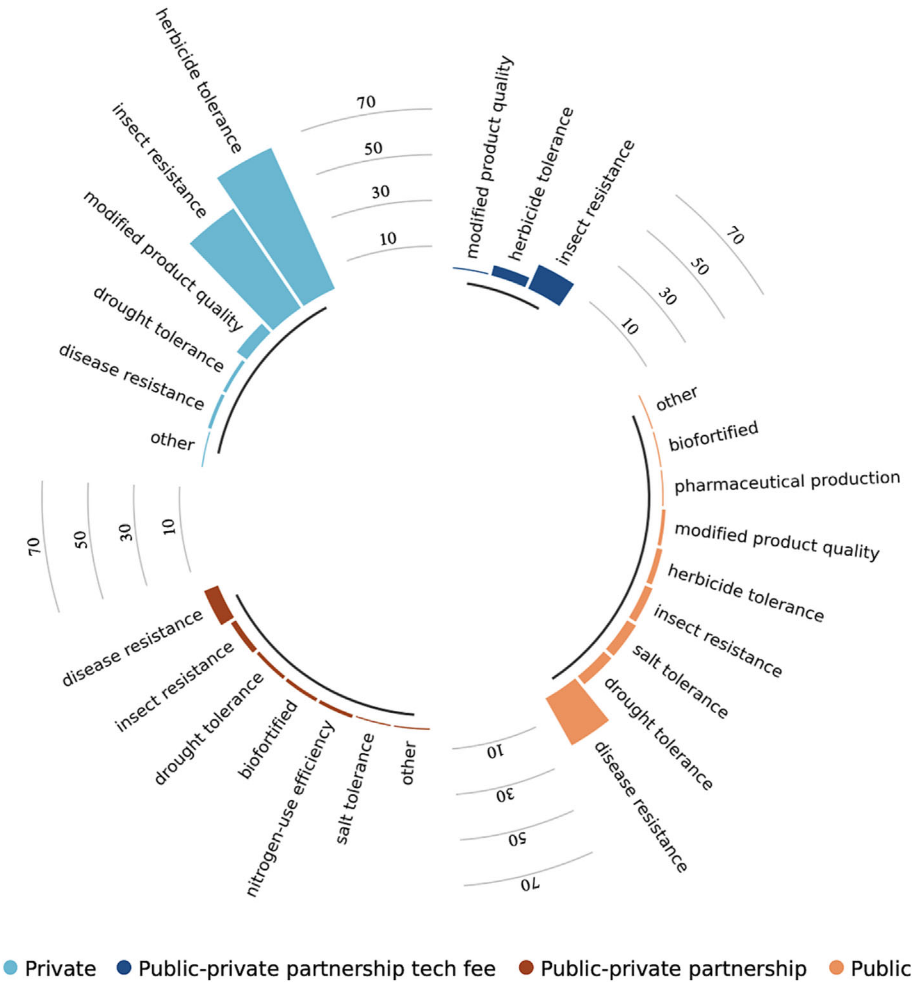

FIGURE 3 Genetically modified (GM) crop varieties sorted by trait and categorized by organizational groups in Africa. In some rare cases, GM crop varieties may be counted more than once given their deployment in different countries under different organizational arrangements. Trait counts contain all traits from multi-trait GM crop varieties. See Methods S1 for how different traits were grouped into trait categories.

private companies and/or PPPs that charge a technology fee. Only one GM crop variety from a PPP has reached the hands of farmers, PBR cowpea in Nigeria. No publicly-driven GM crop research has been commercialized. A majority, or 60.9%, of public GM crop projects have been suspended. The status of a sizable portion, or 71.8%, of private GM crop development is unknown.

The majority of GM crop variety research and development for Africa is conducted either outside of Africa or with partners outside of Africa (see Figure 5). No GM crop developed exclusively by African-based organizations has been approved or commercialized. Most, or 77.8%, of exclusively African-led GM crop research and development has been suspended.

3.1 | Toward understanding the status and efficacy of PPP GM crop R&D for smallholder farmers in Africa

3.1.1 | Extent and focus

Several major takeaways are clear from this examination of GM crop research and development in Africa. The first two are the relatively slow pace of GM crop research and development and its geographic concentration in only a few countries. After first arriving in South Africa in 1996, GM crops have made little progress on the continent, with research only touching 19 of Africa's 55 countries, and only 11 of which continue with active research. When counting research on crops with an unknown status, over 80% is conducted in just five countries, with South Africa home to over half of all GM crop research. Another key takeaway is the dominance of the GM crops research landscape by private companies. Private research alone accounts for 53% of all developed GM crop varieties. When adding PPP tech fee research, which is often dominated by private partners, this number grows slightly to 60%.

Notwithstanding the dominance of private research, public entities have made some important, though geographically-concentrated, contributions to GM crop research and development in Africa. Public research on GM crop development has been conducted in 10 countries. Over half of that research, however, has occurred in only two African countries, South Africa and Egypt, both of which have some of the most robust public research institutions and funding on the continent. Those countries where public research has been conducted on four or more GM crop varieties, in Tunisia, Uganda, and Kenya, also have comparatively robust public research institutions. The mBio dataset appears to confirm what was anticipated in the literature—that private institutions would dominate research and development, and public entities would struggle to conduct their own GM crop research and development.

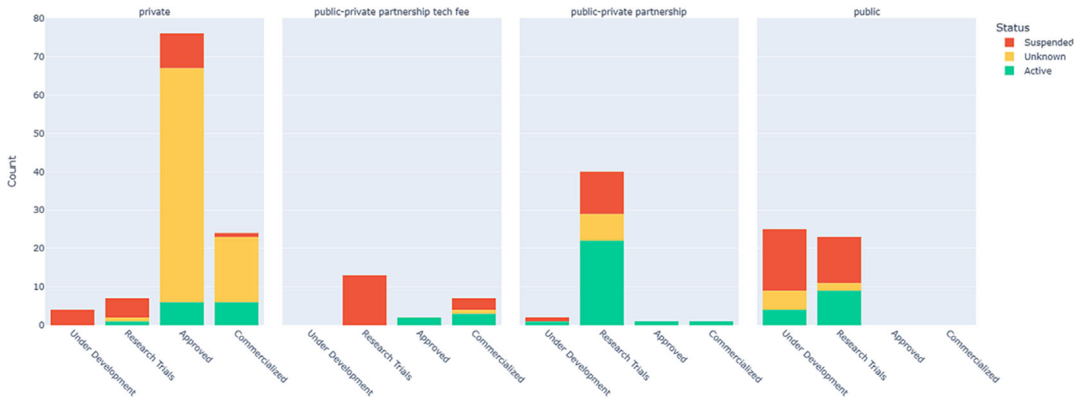

FIGURE 4 Development stage and status of genetically modified (GM) crop varieties categorized by organizational groups in Africa. Development stage represents the current and/or furthest stage of verified development of a GM crop variety. Status refers to whether the GM crop variety is currently active, or whether research or use has been suspended. In some cases, a unique GM crop variety is counted multiple times according to the number of countries in which it is being developed. In such cases, these unique varieties reflect the particular development stage and status in each specific country.

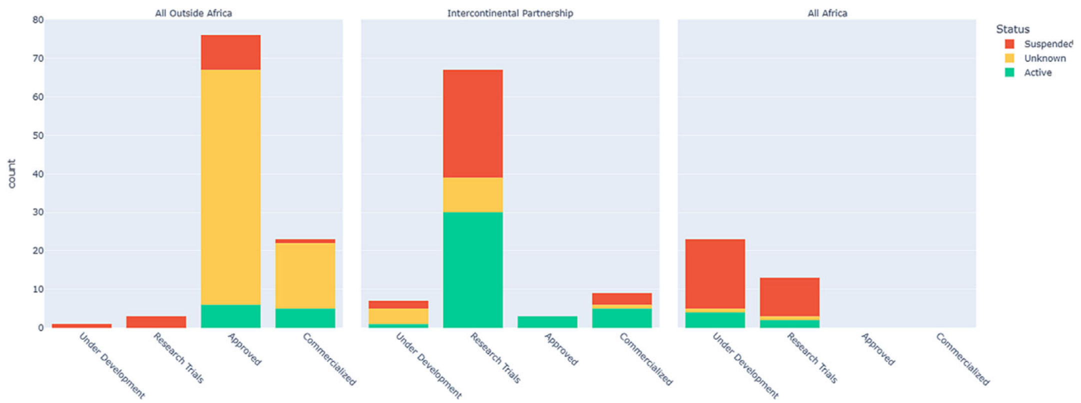

FIGURE 5 Development stage and status of genetically modified (GM) crop varieties categorized by the geographic location of the developing institutions. "All Africa" refers to GM crop variety research and development that is entirely driven by organizations based in Africa. "Intercontinental partnership" refers to GM crop variety research and development with at least one organization geographically based in Africa and at least one organization geographically based outside of Africa. "All outside Africa" refers to GM crop variety research and development by one or more institutions based entirely outside of Africa. Development stage represents the current and/or furthest stage of verified development of a GM crop variety. Status refers to whether the GM crop is currently active, or whether research or use has been suspended. In some cases, a unique GM crop variety is counted multiple times according to the number of countries in which it is being developed. In such cases, these unique varieties reflect the particular development stage and status in each specific country.

The organizational fix to bring about greater GM crop research and development for poor smallholder farmers—PPPs—continues to be limited in scope. PPPs occupy a relatively small portion of the overall GM crop research and development in Africa, or 16.3% of total GM crop varieties under some form of research and development. This research is best understood by splitting the PPP group according to whether a technology fee will be charged to access the GM seeds. PPPs that charge a tech fee are generally composed of private company-driven cooperative agreements, which seek to repurpose and commercialize existing crop technologies. PPPs without a tech fee are qualitatively distinct, since they create agreements and usher funding with the purpose of developing new crop varieties and traits. This latter group is responsible for developing only 8.7% of the total GM crop varieties developed in Africa.

One clear advancement from both PPPs without a tech fee and public institutions is the shift in GM crop research and development toward those crops and traits that are more appropriate for poor smallholder farmers. This shift toward pro-poor crops and traits has long been a goal for many observers concerned that breeding efforts were not sufficiently focused on the needs of marginalized farmers (Baranski & Ollenburger, 2020; Flora & Flora, 1989). Many such breeding reform advocates claim that if research is directed to what can be called a "peasant-based strategy," where traits such as drought tolerance and disease resistance are the focus of research efforts (Boyce, 2011), then new breeding efforts, and specifically GM crops, can, in principle, benefit poor smallholder farmers.

If this is true, then PPPs seem up to the task. PPPs without a tech fee are predominantly organized around crops—sorghum, cowpea, rice, maize—and traits—drought tolerance, disease resistance—that are likely to be more relevant for poor smallholder farmers. Public research is on an even wider set of crops and traits, many of which also appear to be oriented toward crops and traits that have not been the subject of private research, including: apple, banana, canola, cassava, chickpea, enset, fava, grapevine, maize, melon, potato, soybean, squash, strawberry, sugarcane, sweet potato, tobacco, tomato, and wheat.[9] Moreover, the selection of traits is far more diverse than private research and attends more to development goals that are appropriate for small farmers. These include, among others, salt tolerance, drought tolerance, and biofortification, traits that are not the major focus of privately developed and commercially available GM crop varieties in Africa. Early research on gene editing programs confirms a similar trend of focusing on smallholder relevant crops and traits (Beumer & de Roij, 2023).

It is important to note that the status of a sizable portion of private GM crop research and development is unknown. First, much of this work—especially that in the R&D phases—is simply not reported. Unlike PPPs that often have public-facing components—grants, organizational reports, press conferences—private actors do not necessarily share public updates on their research work. Second, that which *is* reported is often through applications to a country's national biosafety authority, an agency tasked with overseeing all approvals for field trials and commercialization of products. Important here is the distinction of "approval." Actors—whether private or otherwise—must submit applications for approval for commercialization, but when approval is gained, it is unclear, in many instances, whether these crops will move to commercialization. In other words, an approval does not necessarily mean that a crop becomes available commercially. Moreover, approvals may be time-limited, meaning that a reported approval is not necessarily an active one.

3.1.2 | Commercialization

A major distinction between private, PPP and publicly-developed GM crops is on the question of commercialization. Aside from a few notable exceptions developed by PPPs, private companies have developed the only commercially-available GM crops in Africa. The mBio dataset offers some insight into why that is the case and provides a basis to raise further questions about what may be inhibiting successful commercializations from PPPs and public research.

Most commercially-available GM crops are those crop technologies that have been shown to perform in other global regions. Two traits—herbicide tolerance and pest resistance—are found on all currently commercialized GM crop varieties in Africa. Three crops—soy, cotton, and maize—comprise all but one of the currently commercialized GM crop varieties in Africa. In other words, those crops and traits that have been geared toward large-scale commercial growers in other regions of the world are essentially the only current GM crop varieties available to African farmers. The vast majority of these have been developed solely by private companies, and in one country, South Africa. The most recent year where data is available, 2019, showed that South Africa comprised 87% of the area of GM crops planted across the continent—all of which come from private companies (ISAAA, 2019). Underlining the dominance of South Africa, a recent review of the global benefits of GM crops only counted the benefits accrued by South Africa farmers when calculating total 2020 benefits for the continent, given the relatively minor contributions of other African countries (Brookes, 2022).

PPPs have contributed some commercialized crops, but they all use the same one or multi-gene Bt pest resistant trait. PPPs that charge a technology fee have commercialized Bt cotton varieties in four countries, Burkina Faso, Kenya, Malawi, and Eswatini. The only PPP non-tech fee commercialized GM crop is PBR cowpea—which contains a single Bt gene trait for pest resistance—that has already been shown to work in other crops, and repurposed for use in cowpea. None of the experimental traits—including salt tolerance, drought tolerance, biofortification, or even disease resistance—have yet to reach the hands of farmers. Moreover, no publicly-led GM crop research and development has led to a commercialization.

This raises two important questions: are poor smallholder farmers currently (or in the future) drawing benefit from GM crop research and development, and what is hindering PPPs and public entities from developing and commercializing those GM crop technologies that are directed to poor smallholder farmers? The two sections below draw from the mBio dataset and related research to provide insights into these questions.

3.1.3 | Adapted to poor smallholder farmers?

In principle, a privately-developed GM crop with pest resistance or herbicide tolerance traits is not necessarily maladapted to poor smallholder farmers. The appropriateness of the particular crop variety would depend on a number of factors including, but not limited to, the characteristics of the crop variety, the goals of the particular farmer or farming household, access to credit, land, labor and inputs, and the capital intensity of the farming operation, among others. In other words, the fact that only privately developed GM crops with few traits and a slim number of crops predominate, does not necessarily foreclose poor small farmers benefiting from currently commercialized GM crops.

Some of the aforementioned crop varieties—most notably Bt cotton and Bt maize—have been enrolled in efforts to directly target smallholder farmers. The most prominent of these efforts have been the introduction of Bt cotton in the Makhathini Flats of South Africa in 1998, and later in Burkina Faso in 2008. Both of these introductions demonstrated initial successes in propelling the adoption of GM seed by poor smallholder farmers but later had difficulties sustaining those rates and profitable performance. The most recent research signals that poor smallholder cotton farmers in South Africa have essentially stopped growing Bt cotton. In Burkina Faso, Bt cotton was discontinued altogether due to the inferior lint quality of the GM variety, which led to significant economic losses for Burkinabè cotton companies (Dowd-Uribe & Schnurr, 2016).

[9]Enset and fava were developed by CGIAR institutions.

The inability to sustain private company-led GM seed adoption for smallholder farmers in South Africa signals the importance of supportive institutions, and principally, credit. What was first thought to be a secure credit market quickly crumbled, resulting in poor smallholder farmers no longer being able to afford the expensive GM seed (Gouse et al., 2005; Schnurr, 2019). Similarly, Bt maize in South Africa—despite its wide appeal among larger and commercially-oriented grows—is only grown by a small percentage of smallholder farmers (Fischer, 2022; Gouse et al., 2016). By contrast, Burkina Faso was able to sustain high levels of adoption due to the presence of a secure credit mechanism (Dowd-Uribe & Schnurr, 2016). In these cases, the security or fragility of credit mechanisms was a crucial factor determining the ability of GM seeds to accrue benefits for poor small farmers.

PPPs that do not charge a technology fee may, in principle, be immune to credit issues, since, presumably, seed prices may not be as high. The limited available evidence suggests, to the contrary, that high seed prices may also be an issue with PPP-developed GM seeds. The Nigerian case is instructive, given that it is the only PPP non-tech fee GM crop that is commercially-available. In a recent forum, project leaders acknowledged the high seed cost of PBR cowpea in Nigeria, though they did not discuss how these high seed costs may be influencing adoption patterns, particularly by poor small farmers (USAID, 2022). Other GM crop introductions, such as Bt cotton in Burkina Faso, have also shown a reticence on the part of marginalized farmers to high cost GM varieties, even when they have robust access to credit (Dowd-Uribe, 2014).

High seed costs associated with PPP-developed GM crops appear linked to a larger institutional issue, namely, the apparent reliance on formal and privately-operated seed companies to deliver GM seeds. Relying on such a strategy could lock-in issues of seed cost, which could limit adoption, particularly for poor small farmers. Moreover, the formal, private seed company-driven seed reproduction and dissemination system is ill-matched with existing pathways of seed reproduction and acquisition for African smallholder farmers. Most acquire their seeds or propagation materials via farmers' seed systems, or the "farm-based seed production and care (including seed selection and storage), processing, distribution and exchange, and procurement of propagating materials" (Zimmerer et al., 2023, pg. 2; McGuire & Sperling, 2016). Seed acquisition and choice is highly heterogeneous for smallholder farmers, and related to a diversity of socio-cultural and economic considerations (Shilomboleni et al., 2023). The best available evidence suggests that at least a majority of PPP non-tech fee crops currently under development will rely on private seed companies to multiply and distribute seeds, including, but not limited to, PBR cowpea, WEMA maize, and disease resistant cassava (Dowd-Uribe, 2023; Schnurr & Dowd-Uribe, 2021). This singular strategy runs counter to the findings of seed systems experts, which suggest that multiple seed delivery strategies and a diversity of improved varieties are needed to meet the existing and future demands of African smallholder farmers (Almekinders et al., 2021).

Even in those cases where GM seeds have been adopted by smallholder farmers, issues related to the interaction between high seed cost and the appropriateness of the variety have been shown to limit profitability for smallholder farmers (Schnurr & Dowd-Uribe, 2021). Growing practices of smallholder farmers often differ considerably from more capital-intensive operations. These differences in growing practices can lead to losses when growing a more expensive GM crop, particularly one that is designed with more commercially-oriented production in mind. Research demonstrates that Bt cotton in South Africa "did not generate sufficient income to expect a tangible and sustainable socio-economic improvement due to the way the crop is currently managed" by smallholder farmers (Hofs et al., 2006, pg. 984). Similarly in Burkina Faso, the growing practices of medium and less-capitalized farmers lead them to sustain losses from growing Bt cotton. It was only the most capitalized farmers who sustained significant economic benefit (Vognan & Fok, 2019). Much of this conversation starts and stops with the type of crop, and the type of trait. But the literature is clear that interactions between seed costs and varietal characteristics beyond the trait are important considerations to consider irrespective of organizational configuration.

These issues of ill-matched variety characteristics appear to extend to PPP non tech-fee programs as well, even despite their focus on smallholder crops. The most prominent issues relate to parent varieties, which are few in number, and often have characteristics that limit their applicability to smallholder farmers. For example, the PBR cowpea project has only commercialized one GM variety, and conducted research on three varieties. All of these varieties exhibit bush-like growing characteristics, which are appropriate for those smallholder cowpea farmers growing cowpeas in monocultures. These varieties are not, however, appropriate for the dominant form of cowpea growing in Burkina Faso—and the one practiced by the smallest and most marginalized farmers—in association with other crops, since it does not creep and cover the ground. These creeping parent varieties have not been part of the GM transformation process (Dowd-Uribe, 2023). Similar parental variety issues exist with other prominent PPP non-tech fee crops—including WEMA maize, which has been placed onto a hybrid as opposed to open pollinated maize parent varieties, and disease resistant matooke banana, which has been placed onto a parent variety ill-suited for many smallholder farmers (Schnurr & Dowd-Uribe, 2021).

In short, the issues that have kept privately developed GM crops from significantly benefiting smallholder farmers—credit and varietal characteristics—are also some of the issues that are likely to make the PPP non-tech fee developed GM varieties ill-suited for many smallholder farmers. High seed costs will likely persist for PPP-developed GM crops, even without a technology fee, making viable credit institutions important for adoption. Moreover, parent variety issues that lock-in features of GM crops also appear to limit their appeal to many poor smallholders. Without greater attention to these issues, PPPs may also have limited appeal for smallholder farmers. But this still fails to explain why PPP research has been relatively confined and slow to commercialize its research for smallholder farmers. We take up this question below.

3.1.4 | What limits PPP-developed GM crop commercialization?

The limited number of PPP GM crop projects, and the limited number of varieties developed in each project, is partly a function of high research and development costs. PPPs only exist due to the significant bilateral and philanthropic assistance—principally from the US Agency for International Development (USAID) and the Bill & Melinda Gates Foundation (Grzenda et al., 2022). These two entities alone have contributed approximately $350 million to GM crop research and development in Africa from 2003 to 2021. This funding includes approximately $261 million of financial support for the AATF (Dowd-Uribe et al., 2022). The substantial capital needed to create and sustain such projects, and the heavy reliance on a small number of key donors, raise doubts about the sustainability of such efforts in the future.

Many point to biosafety regulations as playing a key role in increasing the costs and slowing the time to commercialization of GM crop research and development in Africa. The establishment of biosafety laws and regulatory authorities have taken a long time in many African countries, which, in some cases, may have slowed the permitting and approvals of GM crops on the continent (Komen et al., 2020). Moreover, the high costs associated with complying with these regulations represent a significant hurdle to innovation, principally because they must be borne by the project prior to approval or commercialization (Adenle et al., 2013). Paarlberg (2014) connects the relatively high regulatory costs in Africa to the fears peddled by European and North American environmental organizations and ministries, which he argues led many African nations to adopt more stringent GM regulatory protocols. Gene editing advocates hope that they may avoid many such regulatory costs given the potential lack of foreign DNA in some such crop varieties (Pixley et al., 2019; Zaidi et al., 2019).

GM crop advocates also suggest that misinformation and political pressure dissuade African governments from allowing GM crop research and approving GM crop technologies. For instance, a recent study by Lynas, Adams, and Conrow argues that "false messages about GMOs [in African media coverage]" can "at least partially explain the negative policy environment applied to GM crops and food in most African countries" (2022: 7).[10] Similarly, Smyth et al. (2021) connect the influence of European and North American environmental organizations with the rejections in Zambia and Kenya of GM maize imports. Less appreciated is the significant pressure exerted by the US government and private biotechnology companies on African governments to adopt GM crops and allow for their development and use (Rock, 2022). This pressure is compounded by the significant professional incentives for scientists and research institutions to conduct GM research and demonstrate positive results (Luna & Dowd-Uribe, 2020).

The mBio dataset, which reveals the scope of PPP research across nations with different regulatory regimes and openness to GM crop research and development, opens up space for additional explanations for the slow progress of PPP-led GM crop commercializations to also be considered. All of the major PPPs without a technology fee were established before 2008,[11] yet only one of them has produced a commercialized crop, and only in one of the three project countries—PBR cowpea in Nigeria. Regulatory hurdles may cause some delays, but they cannot fully explain the long time from project formation to crop commercialization. One undervalued explanation for the delays is the significant difficulty in developing the multi-gene traits common in PPP-developed crops, and the considerable time it takes stabilizing such traits on an agronomically- and commercially-viable variety. Such difficulties have been shown with other GM crops with complex traits, such as biofortified Golden Rice (Stone & Glover, 2017).

Related but underappreciated is the issue of power relations, which can play a unique role in PPPs constituting an additional hurdle to commercialization. Power relations—by which we mean decision making, patent holding, and access to- and oversight of- resources—feature heavily in the qualitative literature on GM crops in Africa (Harsh & Smith, 2007; Luna & Dowd-Uribe, 2020; Schnurr, 2019). On decision making; while PPPs feature public African institutions (and at times, multiple institutions), it is unclear how decision-making regarding important project features such as crop variety and trait are made.

Examples of how power relations can affect PPP research can be seen in Ghana. A PPP tech fee project between Monsanto and the Council for Scientific Research Institute conducted several years of field trials of Bt cotton, only for the private partner to eventually pull out of the project in 2016 (Rock, 2022). In other words, the crop failed to reach commercialization not because of lack of performance, but rather, because the patent holder decided to pull the plug on the project. A different PPP no tech fee project—NEWEST rice—had a similar fate. NEWEST rice received principal funding from the US Agency for International Development from 2008 until 2021, and went through field trials in Ghana and other project countries. But the NEWEST rice project came to a halt when donors decided not to renew funding in 2022, despite not having yet produced a product for market (AATF, 2022: 31). This provides an example of both how donors drive key decisions and the dependence of projects on donor funding.

Other research on biofortified and disease resistant banana programs in Uganda show that donors prioritized biofortification over the farmer-preferred trait of disease resistance, indicating the power of donors to drive decision-making (Schnurr et al., 2020). As mentioned above, research on the PBR cowpea shows that varieties chosen for modification are varieties preferred by medium-to-large-scale commercial farmers in Burkina Faso, raising questions around whether the crop will be grown by smallholder farmers (Dowd-Uribe, 2023).

These instances where donors have shaped program directives reflect some of the dynamics in the early critical literature on PPPs. Writing before the majority of PPPs were formed in Africa, Tripp (2002) cautioned that PPPs do not necessarily lead to pro-poor outcomes, particularly given linkages to private seed companies, and incentives to produce profitable technologies. In other words, these seemingly neutral organizational fixes to address the institutional

[10]It is important to note that while Lynas et al. (2022) suggest a causational link between misinformation and policymaking, their research does not measure nor empirically establish such a link.

[11]PBR cowpea in 2002 (Ezezika & Daar, 2012); Virca Plus in 2005 (Taylor et al., 2012); ABS in 2005 (Africa Harvest Biotech Foundation International, 2007); WEMA maize in 2008 (Oikeh et al., 2014); NEWEST in 2008 (AATF, 2023).

hurdles of development pro-poor biotechnologies could have inherent power dynamics, limiting the ability of projects to reach their goals. The myth of PPPs as devoid of complex dynamics was, more recently, discredited by Rock and Schurman (2020), who shed new light on the intricacies of the relationships between private technology holders, intermediary organizations, public research institutions, and researchers. Taken together, the cases described above show how the complexities and power inequities cautioned previously can be best understood as fundamental features of PPPs, which deserve more scrutiny. Moreover, they demonstrate with greater clarity how biotechnology PPPs bring a series of dynamics, which have been shown to constrain their potential to deliver appropriate technologies for poor and marginalized smallholder farmers.

In sum, PPPs offer some potential but remain constrained by other challenges. In many circumstances, these challenges are similar to public research efforts, where seed multiplication and dissemination are key bottlenecks. Other challenges relate to the sustainability of finance for these programs and the power that donors have to shape these projects to their prerogatives. Relatedly, specific challenges include ownership over the programs, particularly for African partners, and the suitability of crop variety development for smallholder farmers.

4 | CONCLUSION

At the turn of the 21st century, substantial discussion over how to develop and commercialize GM crops for African smallholder farmers echoed through the offices of donors, governments, firms, and academics. Acknowledging the challenges that private and publicly-driven GM crop research had in terms of delivering GM crops for smallholder farmers, proponents turned to PPPs as a way to bridge the gap between privately-held technology and pro-poor GM crop breeding. In the time since, there have been significant resources pledged to PPPs, but limited research into their outcomes. In this research, we draw from the mBio database—a repository of data on GM crops in Africa—to analyze PPPs across the continent, and assess their extent and ability to deliver GM crops for smallholder farmers.

We found that PPPs have unlocked significant funding for research on new traits neglected by private companies and on crops that are cultivated by poor smallholder farmers. Disease resistance, biofortification, nitrogen fixation, and drought tolerance have all been the focus of different PPP projects. These traits are being bred into a diversity of crops grown by smallholder farmers, many of which have been neglected by agricultural research. In this sense, PPPs have succeeded as an organizational solution to a set of institutional problems that have plagued the development of GM crops in Africa, namely, meager public agricultural research funding, and the issue of privately-held IPR limiting pro-poor crop breeding.

Notwithstanding these important gains, PPP-developed GM crop varieties have yet to reach the hands of smallholder farmers in Africa, with the exception of PPP-developed PBR cowpea in Nigeria. Many of the proposed reasons for this lag may play a role, including the limited geographic scope and slow pace of biosafety law establishment, assorted regulatory burdens, and media campaigns to cause hesitation among African leaders to push these projects forward. An underappreciated explanation that becomes clear by zooming out of individual projects is the considerable effort and time it takes to develop multigene traits, which are the focus of much PPP-driven research.

It is not yet clear whether these crops and traits will be ready, and when they are, whether they will have the intended effects for smallholder farmers. The organizational fix of PPPs for the institutional hurdles associated with financing and IPR does not appear to set up PPPs to surmount other institutional challenges that have plagued the appropriateness of privately-developed GM crops for poor smallholder farmers. Privately-developed GM crops have struggled to sustainably reach small farmers due to high seed costs, a lack of attention to institutional context, most notably credit, and varietal development that limits their appropriateness. Early indications are that PPPs will rely on formal seed systems for seed delivery, may also suffer from comparatively high seed costs, have similar issues with varietal development, and generally neglect the institutional context needed to foment a more equitable adoption. Moreover, PPPs appear to be prone to unequal power-relations among partners, including a disproportionate level of influence exerted by donors and private firms.

What emerges from this analysis is a more nuanced and wider view of GM crop PPPs in Africa. PPP have successfully bridged some key issues related to GM crop development in Africa by linking privately-held IPR and significant monetary support with poorly-funded public research institutes. However, it is not yet clear whether these advances will be sustainable or sufficient to promote a significant footprint of pro-poor PPP-developed crop varieties that reaches, and makes gains for, poor smallholder farmers.

AUTHOR CONTRIBUTIONS

Conceptualization: Brian Dowd-Uribe and Joeva Sean Rock. *Data collection*: Brian Dowd-Uribe, Joeva Sean Rock, and Trevor Spreadbury. *Data analysis*: Brian Dowd-Uribe, Joeva Sean Rock, Trevor Spreadbury, Patricia Chiril, and David Uminsky. *Figures—conceptualization*: Brian Dowd-Uribe, Joeva Sean Rock, Trevor Spreadbury, and Patricia Chiril. *Figures—design*: Trevor Spreadbury and Patricia Chiril. *Writing—original draft*: Brian Dowd-Uribe and Joeva Sean Rock. *Writing—review and editing*: Brian Dowd-Uribe, Joeva Sean Rock, Trevor Spreadbury, and Patricia Chiril.

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CONFLICT OF INTEREST STATEMENT

The authors report no conflict of interests.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the Mapping Biotechnologies in Africa Project website at www.mbioproject.org.

ORCID

Joeva Sean Rock https://orcid.org/0000-0003-1746-5499
Trevor Spreadbury https://orcid.org/0000-0002-0874-3883
Patricia Chiril https://orcid.org/0000-0002-0172-871X
David Uminsky https://orcid.org/0000-0002-4532-8355

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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