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Reassessing the Cost-Effectiveness of High-Provitamin A Bananas to Reduce Vitamin A Deficiency in Uganda

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There are two high-provitamin A (pVA) banana-based interventions potentially available in Uganda—biofortified genetically modified (GM) banana and fast-tracked banana landraces from outside Uganda that are naturally high in provitamin A (nHpVA). Based on the newest country statistics and using adoption scenarios obtained through focus group discussions and expert interviews, we assess obstacles and opportunities for adoption as well as cost-effectiveness of these interventions. In two alternative scenarios for the GM banana (M9 matooke), we assume 40% and 64% adoption rates, which would result in US$29,374,151 and US$63,259,415 in income saved, respectively. As an alternative, for the symmetrical scenarios, we calculate that if the nHpVA banana (Apantu plantain, native of Ghana) were to be adopted, US$46,100,148 and US$76,364,988 in income would be saved. Taking into account the full cost of R&D, we estimate that the M9 matooke could save one disability-adjusted life year (DALY) at a cost of US$67.37 at best and US$145.09 at worst. We estimate that the Apantu plantain could save one DALY at a cost of US$50.54 at best and US$83.72 at worst. Our DALY analysis estimates that all assessed HpVA banana interventions are extremely cost-effective in all scenarios, following both the World Bank's and the WHO criteria. Nevertheless, successful interventions would require extensive promotion campaigns and shifts in agricultural value chains.

Keywords: DALY, Uganda, nutrition-sensitive agriculture, high-provitamin A banana, vitamin A deficiency

INTRODUCTION

Between 2001 and 2006, Uganda managed to significantly improve its vitamin A deficiency (VAD) rates from 28% among children 6–59 months and 52% among women of reproductive age (WRA) in 2001, to 20% in under-fives and 19% among WRA in 2006 (UBOS, 2001; UBOS and Macro International, 2007; FANTA-2, 2010). In 2011, UDHS 2011 (UBOS and ICF, 2012) reported that VAD levels among children 6–59 months had increased to 33% (UBOS and ICF, 2012), although data in the 2016 UDHS report a significant decline to 9% (UBOS and ICF, 2018). Despite the encouraging trend in VAD, only 15% of children 6–23 months were fed the minimum acceptable diets with only about 30% meeting their minimum dietary diversity and 40% meeting the minimum meal frequency (UBOS and ICF, 2018). Therefore, in an effort to further decrease VAD through increased access to diverse and more nutritious food options, this paper explores whether VAD mitigation strategies touted in past years using high-provitamin A (HpVA) bananas would still be appropriate and cost-effective for Ugandans in 2021 and beyond.

Most households in sub-Saharan Africa rely on monotonous diets mainly based on carbohydrate-rich staples with little or no animal protein, fruits, and vegetables (Ekpa et al., 2019), thus putting them at risk of VAD and other micronutrient deficiencies, a concept known as "hidden hunger." A diversified, nutritious diet is the best way to prevent VAD, but this is usually a challenge for many low-income people to implement (Bouis and Saltzman, 2017). Introducing substitutes for staple foods rich in vitamin A into the farming systems and diet can sustainably combat VAD in developing contexts while also better meeting people's caloric needs (Fungo et al., 2010; Bouis, 2018; Garg et al., 2018). These interventions can cost a fraction of national supplementation programs, if start-up costs can be accommodated (Beyer, 2010; Meenakshi et al., 2010; Garg et al., 2018). In Uganda, diets are based on the starchy staple East African Highland banana (EAHB), locally called "matooke." It is a cooking banana that is a poor source of pVA (Dale et al., 2017). Dessert bananas and plantains, consumed mostly as snacks, are also present in Ugandans' fields and diets. As a result, banana has been pinpointed as a powerful and feasible entry point to improve nutrition in Uganda.

There are two options for obtaining a nutritionally improved staple food: by screening existing cultivars to identify and promote those with high nutritional content or through biofortification of popular staples. Biofortification is the creation of nutritionally enhanced cultivars via conventional breeding, transgenic breeding (Saltzman et al., 2013; Mbabazi, 2015), or agronomic fortification methods (Garcia-Casal et al., 2016) in order to eliminate hidden hunger. The conventional breeding of bananas is difficult and costly because of their vegetative reproduction. Transgenesis, or genetic modification (GM), adds one or more genes to an already desirable cultivar and is a straightforward way to successfully alter a banana cultivar (Dale et al., 2017). The large-scale adoption of a new GM banana cultivar requires infrastructure, biosafety regulatory approval, and the buy-in of the targeted communities. Fast-tracking existing cultivars that are naturally high in provitamin A (nHpVA) can be a very cost-effective alternative to biofortification (Davey et al., 2009; Garg et al., 2018). Because of the complexity in finding appropriate banana cultivars for nutrition-sensitive agriculture, multiple options for any one context must be considered and tested.

For the Ugandan market, both biofortification and fast-tracking extant HpVA bananas are available intervention options. NARO developed a biofortified EAHB cultivar, genetically modified (GM) to be rich in vitamin A, that is analogous to a traditional cooking banana (Paul et al., 2018). In addition to being HpVA, the hybrid has resistance to pests and diseases (black sigatoka nematode and banana weevil) (Nowakunda et al., 2015), which would likely be an important factor driving up its adoption, in particular in parts of Uganda where pests and diseases are a problem. On the other hand, this cultivar was found to have slightly lower than traditional matooke varieties taste scores following evaluations (Akankwasa et al., 2013), which would likely cause a negative effect on the adoption rates.

This GM banana cannot be fully released to the market until the Ugandan government approves it (Paul et al., 2018). Ugandan President Museveni rejected the Genetic Engineering Regulatory Bill for a second time in July 2019 due to concerns that the law inadequately protects smallholders and the environment from agribusiness and GM technology (Wassajja and Mulondo, 2019). However, by March of 2020, the President supported the bill and encouraged the Parliament to pass it (Bendana, 2020). Surveyed Ugandan consumers indicate that they would buy GM bananas if they can believe in their nutritional value, with the rural consumers assessing the GM bananas more positively than consumers in urban areas (Kikulwe et al., 2010).

For the second intervention option on fast tracking of nHpVA banana varieties, Bioversity International screened over 400 varieties of banana for high levels of provitamin A carotenoids (pVACs) as options for food security programs in the Global South, in collaboration with research partners (Tutwiler, 2016). Eleven varieties with carotenoid levels high enough to meet a child's daily recommended vitamin A intake following consumption of a single banana were introduced for trials in Burundi and the Democratic Republic of the Congo (DRC) (Ekesa et al., 2015). Initial feedback about agronomic performance and social acceptance was positive in these two countries, with farmers showing strong willingness to grow and share the introduced cultivars of provitamin A-rich plantain and dessert bananas with their neighbors and friends (Ekesa et al., 2017).

Despite these positive results, their uptake and adoption rates in Uganda are likely to differ significantly, since these plantains are not EAHB, Ugandans' staple banana type. Ugandans consume large quantities of EAHB (cooking banana) in their homes. Compared to matooke, plantain constitutes a much smaller component of diets among rural consumers at household level in central and western Uganda. The plantains, locally referred to as "gonja," are mainly cultivated for sale targeting city restaurants, private sector (make plantain crisps for supermarkets) street food vendors, and roadside/highway snacks for travelers, so basically mainly consumed by urban, peri/urban dwellers, and travelers across the country, thus still constituting a significant population. In addition, with the high concentration of pVACs, even a small portion of the plantain banana could have a high impact on nutrition. The other strength of plantain is that it can be fried, boiled, or roasted, thus making it a dish economically viable for both rural and urban populations. The observed low consumption among rural populations is because the need for income is greater than the nutrient need. Therefore, increased awareness creation and advocacy on the need to diversify the farming system and diet system supported by increased access to the planting materials could be a key to ensuring that both income and nutrient needs are achieved.

While significant initial investments in both the banana projects (GM and nHpVA) have already been made, the road to an implementation phase in Uganda is still long. It is therefore crucial to explore future, hypothetical successes and pitfalls, and assess the cost-effectiveness of both interventions. From the decision makers' perspective, cost-effectiveness is an important metric when evaluating an intervention. Fiedler et al. (2013) used a disability-adjusted life year (DALY) framework to argue that vitamin A deficiency in Uganda could be reduced in a cost-effective manner through the introduction of GM, biofortified bananas. However, the VAD situation has already and independently improved since this 2013 study, while the GM banana has yet to arrive on the Ugandan market. Meanwhile, the cost-effectiveness of deploying a nHpVA banana cultivar has not been assessed at all. A cost-effectiveness analysis (CEA) of both the GM and nHpVA bananas, incorporating the most recent national VAD statistics and reasonable project timeframes, is therefore the innovation provided by our study.

It is widely hypothesized that HpVA bananas can greatly reduce VAD in both rural and urban areas of Uganda if implemented as part of a holistic food security program (Fungo, 2009; Paul et al., 2018; Amah et al., 2019). Our current study updates this discussion with a mixed method ex-ante impact assessment of HPVA bananas in the Ugandan context. We base our analysis on the assessment of potential adoption rates obtained through focus group discussions (FGDs) and expert interviews conducted in 2018 with selected banana producers and consumers in central and western Uganda. We provide a DALY calculation and CEA for the proposed banana intervention scenarios. Using up-to-date statistics for transparent, shareable calculations, the DALY framework quantifies the current burden of VAD within Uganda. We subsequently project how this burden could be reduced by introducing a GM banana or one of the nHpVA cultivars tested by Ekesa et al. (2015, 2017) and outline the economics of these interventions. All cultivars evaluated by Ekesa et al. (2015) showed significantly higher pVA carotenoid levels than popular local cultivars of the same genomic group and type. In our evaluation, for transparency of the results, we selected only one nHpVA—Apantu; however, some other cultivars proposed by Ekesa et al. (2015, 2017) would yield similar cost–benefit ratios as a result of almost identical costs and similar pVACs content with the Apantu plantain.

These DALY calculations are offered as an update and extension to the work done by Davey et al. (2009) and Fiedler et al. (2013). In the **Supplementary Material**, we provide the step-by-step process of calculating DALYs and their cost-effectiveness, as a methodological guide, so that other researchers can replicate it for other analyses.

Specifically, we answered the following research questions:

1. What is the potential supply and demand, differentiated by men, women, and youth, for vitamin A-rich bananas in Uganda? How does this compare with locally produced bananas?
2. How much could GM, HpVA matooke, or nHpVA banana reduce vitamin A deficiency in Uganda?
3. How cost-effective would a GM biofortification or nHpVA banana agricultural/nutrition program in Uganda be?

MATERIALS AND METHODS

Expert Interviews and FGDs

Anonymized expert interviews and FGDs were conducted in September and October of 2018. These interviews and FGDs served to collect qualitative and quantitative information about VAD awareness and potential demand for naturally occurring and GM HpVA bananas in central and western Uganda.

For the FGDs, five districts were sampled—Bushenyi, Isingiro, Luwero, Mukono, and Kampala. Aside from the urban sample from Kampala, two districts from each region, then two sub-counties, and then two parishes were randomly selected to ultimately arrive at three FGDs from each parish. The anonymized participants of the FGDs, categorized into women (age ranging from 30 to 65 years), youth (men and women ranging from 18 to 29), and men (age ranging from 30 to 65 years), were randomly selected from village household lists supplied by the local government. In total, data were collected from 510 Ugandan banana producers and consumers in the rural areas, and 96 non-farmer banana consumers in Kampala city.

Enumerators collected anonymous responses from FGD participants by assigning each person a number to cite before answering a question. FGD participants were told about the characteristics of the vitamin A-rich bananas: the GM banana is very similar to the local EAHB matooke, and the nHpVA banana is a plantain. Data were captured via voting and structured questions, with each FGD lasting approximately 3 h. Five of the FGDs from the sampled parishes were excluded due to data quality reasons. The final dataset consists of responses from 19 female FGDs, 16 mixed-gender youth FGDs, and 17 male FGDs and was translated from Luganda and Runyankole into English.

To complement the FGDs, seven anonymous expert informants were interviewed, two of whom representing agricultural research institutions and the other five representing Uganda's Ministry of Agriculture. These questionnaires asked the informants to identify cultural and agricultural parameters that should be considered when introducing the different HpVA cultivars to Ugandans. The expert informants were also asked to estimate potential adoption rates of the naturally occurring and GM HpVA banana varieties and to estimate the popularity of various dissemination methods at the national level.

The data collected through expert interviews and FGDs were analyzed using qualitative and quantitative methods. The results from both data collections were used to inform multiple further analyses and considerations. When projecting how Ugandans' health could be impacted by the introduction of pVA banana, a key consideration is to what extent a new banana would be incorporated into a household's meals and farming strategies. To this end, the substitution rate of a new banana replacing the local matooke variety was assigned by averaging the experts' estimates of the maximum proportion of local matooke that would be replaced by the HpVA cultivars. The FGDs gave us exceptional insight into what Ugandan farmers are interested in growing and consuming, including quantitative data, which we used to estimate how vitamin A intake could vary, given the introduction of a GM matooke or a nHpVA plantain. After measuring how the HpVA cultivars could impact VAD in Uganda, and at what cost, the knowledge and opinions expressed by the people interviewed provided crucial context for our policy recommendations.

Disability-Adjusted Life Years

DALYs quantify the burden of a given health problem by estimating how many years of life a person loses to disabilities or death caused by disease. As an index, DALYs enable normalization between different diseases so that policy makers and advisors can directly compare the magnitude of, for example, diabetes vs. hypertension in a given population, and decide how best to focus their resources. The second (optional) step of a DALY analysis is to calculate the economic efficiency of various health interventions via the metric of "DALYs saved per dollar spent" (Stein et al., 2005). Our DALY calculations quantify how many years of people's lives could be saved if different varieties of HpVA bananas were to be introduced in Uganda and the cost-effectiveness of such interventions. For this study, the baseline DALYs lost to VAD were calculated combining the methodologies of Stein et al. (2005), Stein (2006), and Zimmermann and Qaim (2004), mostly drawing upon Ugandan national statistics and World Bank data. Other parameters used in the DALY analysis were elicited from the experts and the FGDs. See the **Appendix** for a detailed stepwise explanation of the entire process.

DALYs—Baseline and Two Alternative High-pVA Banana Scenarios

The baseline DALYs are the sum of all the years of life lost to disease, all the years of life spent with a temporary disability from disease, and all the years of life spent with a permanent disability as an outcome of disease. DALYs lost are calculated on an annual basis. In the case of vitamin A deficiency, the first part of the calculation measures how many DALYs are lost by the deaths of preschool children (under the age of five) to VAD. The second component calculates the DALYs lost to the temporary disabilities that are part of the VAD burden. The third component calculates how many DALYs are lost to permanent disabilities resulting from VAD. See formula 1 in the **Appendix** to understand how baseline DALYs were calculated. The burden of VAD is largely placed on preschool children; the only aspect of our DALY analysis that incorporates numbers from pregnant and lactating women is in the second component of the formula, when quantifying the burden of night blindness. The DALY formula and the step-by-step explanation of the entire process, including all data sources, are available in **Appendix A**.

We considered two banana cultivars for potential interventions:

- M9 matooke: GM, biofortified EAHB
  - One daily portion (300 g) gives a preschool child 57% of RDA (200 μg)
- Apantu: nHpVA plantain
  - One daily portion (100 g) gives a preschool child 118% of RDA (411.9 μg).

The GM matooke, an East African Highland cooking banana, comes from the AAA genome group. Specifically, it is the M9 cultivar that has been tested in Uganda (Mbabazi, 2015). The nHpVA cultivar is the Apantu plantain from Ghana, a False Horn plantain of the AAB genome group (Ekesa et al., 2015). We modeled the impact of these HpVA bananas on Ugandans' VAD burden by creating four hypothetical DALY scenarios, projecting the impact of the Apantu and M9 given pessimistic and optimistic coverage ceilings. Our study thus explored how HpVA plantain and a GM matooke could impact Ugandans' nutritional status.

The Economics of DALYs

After calculating the DALYs lost to VAD under the various scenarios proposed above, the next step was to calculate the financial aspect of the interventions. Given the lack of information about the M9 banana's development costs, program costs were extrapolated by averaging the budget components from a survey of other GM and biofortified food cultivar projects, which at least partially provided financial information. Projects from India (Stein et al., 2007; Bayer et al., 2010), Kenya (Bayer et al., 2010; Levin et al., 2019), the Philippines (Manalo and Ramon, 2007; Bayer et al., 2010), Costa Rica (Bayer et al., 2010), Brazil (Bayer et al., 2010), Uganda (Meenakshi et al., 2007; Davey et al., 2009; Fiedler et al., 2013; Stathers et al., 2015), and South Africa (Bayer et al., 2010) were examined. See **Supplementary Table B1** in Appendix B for an overview of these projects.

Following Fiedler et al. (2013) and Stein et al. (2007), we broke down the program costs of the two HpVA cultivar programs into the following components: (1) Research and Development (at the international level); (2) Adaptive breeding (country-specific); (3) Bio-regulatory-related costs; (4) Promotion campaigns and extension services; (5) Maintenance breeding; and (6) Monitoring and evaluation. These six cost components were used to create eight different budgets based on the above-listed studies, varying by such parameters as expensive adaptive breeding costs or very low costs for promotion and extension services. A detailed breakdown of the seven case studies applied for both the GM and nHpVA banana can be viewed in **Supplementary Table B2** in Appendix B. The only cost component that remained constant was the bio-regulatory expense for GM cultivars, which was applied for the M9 matooke but not the nHpVA Apantu. This one-time expense came from averaging all bio-regulatory costs reported by projects in countries where, like Uganda, GM food crops are not yet legally approved.

The final component of costing out a program is the speed of adoption by the targeted population. We argue that if smallholders are well-supported with trainings and inputs, a speedy timeframe of 7 years to maximum adoption is feasible in Uganda for any appropriate HpVA banana. This 7-year window contrasts with the more conservative adoption curve of 19 years used in the DALY calculation by Fiedler et al. (2013). We started from the adoption curves offered by the informants in our expert interviews, presenting the more conservative estimates. We also cite a study of GM cotton adoption by Indian farmers, where adoption went from 0 to 65% nationwide in 5 years (Stone, 2011, p. 390). According to Vaiknoras et al. (2019, 279), the people of central and western Uganda are likelier to adopt new technologies and adopt them more quickly, given that they are more educated than the national average. Men in the FGDs had one more year

TABLE 1 | Cost components (ranges of estimated yearly costs in USD) and timeframe for both banana scenarios.

	Cost Scenarios					
Phase	**R+D (international)**	**Adaptive breeding (Uganda-specific)**	**Bio-regulatory costs**	**Promotion/Extension**	**Maintenance breeding**	**Monitoring/ Evaluation**
Years	8	5	1	7	7	10
Cost ranges	$54,892.25–$1,600,000	$240,725.40–$800,000	$1,750,000	$169,269.67–$1,882,283	$100,000–$200,000	$93,531.67–$200,000

Bio-regulatory costs apply only to a GM crop. The sources and details of these ranges are provided in ***Supplementary Table B2*** *in Appendix B.*

of education compared to the national standard for their age, while women and male and female youth had three more years of schooling (UBOS and ICF, 2018).

Following de Steur et al. (2012), the CEA of a program divides the total program costs by the total number of DALYs saved by the intervention, factoring in a 3% discount rate. See **Appendix B** for the CEA formula and data on program cost. See **Table 1** for a summary of the data used for the numerator of the CEA formula. To determine the total cost of these HpVA banana interventions, our analysis includes the costs of international research and development (based on similar projects—details in **Supplementary Table B2** of the Appendix). In fact, this full cost could be shared by multiple countries and stakeholders, effectively improving the CEA. Consequently, we also calculated the "Uganda-specific CEA" by eliminating the sunk costs of international research and development; this cost per DALY saved reflects the investment Uganda would have to make to bring the program to fruition from this point forward. The "full CEA" is presented alongside the "Uganda-specific CEA" in section DALYs (Results and Discussion).

By running the eight budgets outlined above and averaging the results, we obtained the average cost per DALY saved, given (1) pessimistic coverage (40% of consumers) and 7 years to peak adoption and (2) optimistic coverage (64% of consumers) and 7 years to peak adoption. The first scenario would be less desirable while the latter would be the best possible way for the program to unfold, being the most nutritionally effective and cost-efficient.

RESULTS AND DISCUSSION

FGDs—Farmers' and Consumers' Perceptions and Potential for Adoption of High-pVA Bananas

The FGDs showed significant differences in VAD awareness levels between genders. At 56% responding "yes," the female FGDs had the highest awareness about vitamin A's importance, while only one-third of youth and male FGDs had heard of vitamin A. The female FGDs had the most wide-ranging knowledge about pVA and VAD implications, while the youth knew the least. Women had the best understanding of pVA's importance for infants and children, while the other two groups did not mention pregnancy or breastfeeding at all (perhaps due to cultural reasons), and children's malnourishment only a few times. Common responses from women included statements like "*It's a brain booster to the young children,*" "*It helps the baby grow well in the mother's womb,*" "*It helps in clear vision,*" and "*it helps the skin look good.*" The youth groups that were aware of vitamin A did not mention benefits during pregnancy but did say "*it helps us be healthy*" and "*it helps us keep good eyesight.*" The male groups who knew of pVA also focused on its benefits to the immune system, with responses like "*It helps with building the immune system that fights against diseases like measles.*" All FGDs had similar rates of accuracy when listing foods rich in pVA; on average, just under half of the foods listed by men, women, and youth were indeed rich in vitamin A.

Plantain has a small share in the diets of rural and smallholder households of central and western Uganda, which was reflected in the FGDs—when asked how many times plantain is eaten in a week, many reported the consumption as "zero," and said that all the cultivated plantain is for cash crop purposes. Among the remaining 14 FGDs that reported some consumption of plantains, the average consumption was less than once a week. These low consumption levels, although mainly attributed to the fact that the respondents were predominantly rural dwellers from smallholder households, could be a significant obstacle in achieving nutritional impact nationwide through the nHpVA banana. However, the participants reported that the plantains are grown for markets, so market demand and prices would be the main driver of adoption. The consumption is concentrated in the cities, where the HpVA plantain could have the highest impact if the adoption is accompanied by awareness creation.

When it comes to GM technology, none of the female FGD respondents had heard of it before. One-third of the male FGDs had heard of GM technology; however, only a third of them had positive ideas about it. Among the youth, half of the FGDs had heard of GM technologies, and out of those, half had positive or neutral attitudes toward it. The rest, similarly to the male groups, worried GM crops would harm people, soil, and local varieties. Overall, the youth had fewer negative ideas about GM technology than the male groups; more youth groups than male FGDs stated that they knew of hybrids, but not of GM technologies.

From information gathered through the FGDs, the maximum adoption rates for the GM banana were estimated at 56% in the western region and around 35% in central Uganda, with an average of 43% for both regions. The regional differences reflect the difference in proportional importance of EAHB as a food crop between western and central smallholders. Looking more closely, we see that the youth FGDs similarly estimated adoption rates in both regions at over 35%. The central region women's FGDs estimated 33% adoption, but western women's FGDs estimated significantly more—64%. The men's groups fell along a similar line, averaging 37% for central households and 66% for the western region. People listed 10 different reasons for being willing and motivated to grow GM banana, including it being a familiar, traditional cooking banana, or wanting to innovate, or for affordability, or growing it as a cash crop, or for its nutritional content. All types of focus groups cited "nutrition" as a main motivator to growing the GM HpVA banana. Women mentioned "nutrition" and "Because it is like our local, traditional banana." For the male groups, "nutrition" was the most frequent response, while for youth, it was "Because it is a cooking banana."

Participants were presented with four different banana market scenarios: only local EAHB, local banana and nHpVA plantain, local banana and GM EAHB, and local banana and both HpVA cultivars. Then they were asked to decide how much of each cultivar they would produce. The overall pattern between the four market scenarios was similar between western and central FGDs. Reflecting the Ugandan preference for matoke over plantain, the production share given to the HpVA plantain was always much smaller than that allotted to the GM matooke. The average share of production given to the GM matooke in the third market scenario was 41.5%, which is just above the pessimistic adoption ceiling used in our DALY calculations.

Expert Interviews—Potential for Adoption of High-pVA Bananas

Among the seven anonymous expert informants interviewed, none was neutral about or contrary to the idea of either banana cultivar being developed or introduced in Uganda—the majority of them strongly supported both the naturally occurring and GM HpVA banana varieties. They expressed support for the development of biofortified seed within Uganda. One person specified: "Because those from other countries may not be able to survive in Uganda." With no reasons provided, experts said southwestern and central farmers were the most likely to adopt GM bananas (eastern and western farmers were also mentioned). Bananas that are naturally high in pVA would only be adopted by central Ugandans because they are "enterprising" and eat plantain more than people in other regions.

Two expert respondents refused to make estimates for questions related to the adoption rates. One of these experts provided the following response: "The end-user is the determining factor. Major determinants for the GM banana will depend on the characteristics of the food, like softness, taste and retention characteristics."

The five experts who were willing to provide numbers predicted that more people would adopt the GM cultivar than the nHpVA overall and that the GM bananas would be adopted more quickly than nHpVA bananas. They assumed the highest adoption of nHpVA bananas among the urban population and school children. The average maximum adoption rate of GM bananas was estimated at 64% and the average maximum adoption rate of nHpVA bananas was estimated at 45%.

DALYs

Baseline DALYs and the HPVA Banana Scenarios: Quantifying the Burden of Vitamin A Deficiency

As per the 2017 World Bank and 2018 Ugandan national statistics, we quantified the current burden of VAD as a loss of 89,559 DALYs. Fiedler et al.'s (2013) DALY analysis, which worked with 2005/06 household survey data, reported the burden as a loss of 166,070 DALYs. This significant improvement in the health of Ugandans over the past decade is an encouraging sign, but there is still an issue of hidden hunger that includes vitamin A deficiency. We then calculated the DALYs lost to VAD under hypothetical, pessimistic, and optimistic adoption scenarios of the M9 (GM) matooke and Apantu plantain. At best, 53,473 DALYs would be lost with the M9 matooke, while at worst, 72,803 DALYs would be lost. For the Apantu plantain, the worst-case scenario would be a loss of 63,262 DALYs and the best-case scenario would lose 45,997 DALYs.

The economic burden of VAD can be translated into the total income that could have been earned during 89,559.4 life years, which corresponds to US$156,997,677, taking Uganda's 2018 gross national income (GNI) per capita, based on purchasing power parity (PPP) (constant 2011 international $). In the pessimistic scenario, which assumes that M9 matooke were adopted by 40% of the population, 18.7% of those life years could be saved, and US$29,374,151 in income would be recovered. In the optimistic scenario, which assumes that the M9 matooke would be adopted by 64% of consumers, 40% of those life years could be saved, which translates into US$63,259,415 of recovered income. As an alternative, we calculate that if the Apantu plantain were adopted by 40% of the population, then 29.4% of those life years could be saved, and US$46,100,148 would be recovered in income. Optimistically, if the Apantu plantain were adopted by 64% of consumers, then 48.6% of those life years and US$76,364,988.61 in income would be recovered. See **Table 2** for the summary of these calculations.

The Economics of the Various High-pVA Programs

As explained in *Materials and Methods*, we assumed a 7-year timeframe to peak adoption for both the GM and nHpVA cultivars while conducting the CEA of the programs. The entire lifespan of each program was 19 years when including international research and development, while the Uganda-specific program costs encompassed 14 years. The costs per DALY saved are listed in **Table 3**. We estimate that the M9 matooke could save one DALY at a cost of US$67.37 at best and US$145.09 at worst. We estimate that the Apantu plantain could save one DALY at a cost of US$50.54 at best and US$83.72 at worst.

Eliminating the international research and development costs, which also reduces the program by 5 years, the Uganda-specific costs per DALY saved are somewhat reduced (see **Table 3**). For the Ugandan CEA, we estimate that the M9 matooke could save one DALY at a cost of US$43.64 at best and US$93.98 at worst. We estimate that the Apantu plantain could save one DALY at a cost of US$30.84 at best and US$51.08 at worst. This Uganda-specific cost per DALY saved by the Apantu plantain is significantly better than the cost-efficiency estimated for the

TABLE 2 | Impact of high-provitamin A cultivars in reducing Uganda's vitamin A deficiency burden.

	DALYs lost to VAD	% of DALYs saved through biofortification	Total income lost to VAD (US$) [Uganda's 2018 GNI per capita, based on PPP (constant 2011 international $)]
Current situation	89,559.4	-	$156,997,677.33
M9 pessimistic scenario	72,802.9	19%	$127,623,526.47
M9 optimistic scenario	53,473.1	40%	$93,738,261.80
Apantu pessimistic scenario	63,261.6	29%	$110,897,529.62
Apantu optimistic scenario	45,997.0	49%	$80,632,688.72

M9 is a GM banana; Apantu is a nHpVA cultivar.

TABLE 3 | Cost per DALY saved by the four HpVA scenarios.

	Pessimistic consumption coverage	Optimistic consumption coverage
Full cost-efficiency analysis		
M9 matooke	$145.09	$67.37
Apantu plantain	$83.72	$50.54
Uganda cost-efficiency analysis		
M9 matooke	$93.98	$43.64
Apantu plantain	$51.08	$30.84

Full Cost includes R&D costs, which are currently sunk costs. Uganda cost-efficiency analysis only accounts for the future costs for implementation in Uganda. M9 is a GM banana, Apantu is a nHpVA cultivar.

nHpVA, non-EAHB by Davey et al. (2009). At US$87 per DALY saved, their Uganda-specific optimistic scenario was less efficient than our study's pessimistic scenario, while their pessimistic scenario was US$513 per DALY saved.

Finally, cost-effectiveness can be compared to the limits offered by the World Bank, where a program is "very cost-effective" if the cost per DALY saved is under US$260, while the World Health Organization rates an intervention as "very cost-effective" if the cost per DALY saved is less than the per capita income (Fiedler et al., 2013). In the case of Uganda, US$1752 (constant 2011 international $) would be the upper limit (The World Bank Group, 2019). The HpVA banana interventions examined are thus very cost-effective in all scenarios, whether one is prioritizing the World Bank's metric or that of WHO. While the cost-effectiveness of a nutrition intervention is an important parameter to consider in decision making, the economics are inextricably linked to and driven by the interests of the people being targeted.

CONCLUSIONS AND POLICY IMPLICATIONS

Based on updated data on VAD prevalence and adoption rates and schemes obtained through FGDs and expert interviews, we find that, despite the limits to adoption in each case, both HpVA banana interventions could be very cost-effective in Uganda in all considered scenarios. The investment that has already been made makes these interventions on promoting adoption of HpVA banana a rather low-hanging fruit in economic terms.

Banana is considered a good candidate for GM—because of its vegetative reproduction, the risk of unintended gene flow to indigenous bananas is very small (Dale et al., 2017; Schnurr et al., 2018). A GM banana is currently controversial among the farmers we interviewed, with many being reluctant to grow it. However, there is a potential for their attitudes to be changed, especially among women who most valued the nutritional benefits of the crop. A banana that, together with improved nutrition, offers improved resilience to pests and diseases would likely be better received by all groups of farmers. Another potential issue to be considered when introducing a GM crop is how it would affect international trade (Frisvold and Reeves, 2015). Agricultural produce constitutes around 60% of Ugandan exports; however, EAHBs are mostly consumed domestically (WTO, 2020).

Golden Rice exemplifies the pitfalls of GM biofortification. Even though from a scientific standpoint the technology was deemed a success, by offering a cost-effective way of saving lives lost to VAD (Stein et al., 2006; Wight, 2019), it turned out to be extremely difficult to obtain varietal approval and release. Anti-GMO laws and sentiment have blocked this cultivar's dissemination, causing 20 years of money and time to be spent on Golden Rice with zero improvement in VAD (Potrykus, 2010; Stokstad, 2019). Dubock (2019) writes that very substantial investments of time and resources are needed to convince scientists, governments, and consumers that cultivars like Golden Rice will be beneficial, contradicting the assertion that biofortification programs are more financially and temporally efficient than traditional approaches. Indeed, the red tape and investment costs surrounding GM cultivars, underpinning producers' and consumers' heavy reservations, remain significant limitations for current and future nutrition programs that include them (Borlaug, 2000; Saltzman et al., 2013; Tohme and Beyer, 2014; Garg et al., 2018; Qaim, 2020).

Apantu plantain could be considered a less controversial alternative to the GM banana. Nutritionally, it is more effective than the M9 matooke, given that it is likely to significantly contribute to Vitamin A requirements where there are low intake levels. However, there is arguably a barrier to adoption of even 100 g of daily per capita plantain consumption, especially among rural smallholder households as it is mainly consumed as street food, in restaurants, and by travelers along the highways across Uganda.

The success of the Apantu program would hinge upon extensive promotion campaigns on the economic and nutritional value of the crop, targeting different consumer segments along the agricultural value chains in both urban and rural settings. In so doing, extra efforts need to be paid in both settings not only to ensure proper dissemination of the Apantu variety but also to address more structural and value chain issues that may hamper its production and commercialization. The strategy to increase consumption of plantains in rural areas would make Apantu even more effective in eradicating VAD. For this purpose, alongside the health awareness campaign, increased access to the planting material and extension services would be needed. As with the GM matooke scenarios, a big shift would need to occur in order for this program to effectively address VAD, despite the cost-effectiveness demonstrated above.

Moreover, the M9 banana could potentially also benefit Burundi and Rwanda that are also fighting VAD (WHO, 2020), making the intervention even more cost-effective by distributing the initial investment over a larger group of beneficiaries. The two countries have high matooke consumption rates (Collins et al., 2013, p. 16–17; WFP, 2018, p. 21–22; WHO, 2020) through which biofortification could reduce high prevalence of VAD. Like Uganda, though, these countries' legal frameworks would cause GM biofortification programs to have long adoption curves (East African Community, 2016). The Apantu plantain could also be considered by other nations that consume plantain and have sizable VAD burdens, such as DRC or Cameroon (WHO, 2020).

Finally, when considering VAD-eradication strategies, we consider it important to target, in the long term, diverse and nutritious diets alongside sustainable food systems that protect and promote agrobiodiversity (Jacobsen et al., 2013; Bioversity International, 2017).

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the authors. The metadata are available in Harvard Dataverse with the following citations: Kozicka et al. (2019a,b).

AUTHOR CONTRIBUTIONS

MK conceived and designed the analysis, contributed analysis tools, performed the analysis, and wrote the paper. JE contributed analysis tools, performed the analysis, and wrote the paper. BE conceived and designed the analysis and contributed analysis tools. SA contributed analysis tools. EK conceived and designed the analysis, supervised data collection, and contributed analysis tools. EG conceived and designed the analysis, guided the study. All authors contributed to the article and approved the submitted version.

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SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2021.649424/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.