Assessing the Benefits of Multi-biofortified Rice in Nigeria and Ghana using the Disability-Adjusted Life Years Framework

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Abstract

Deficiencies in key micronutrients such as Vitamin A, Zinc, and Iron constitute global health challenges in low- and middle-income countries and have been shown to have detrimental impacts on economic development. Existing efforts to address such deficiencies include industrial fortification of processed food and clinical administration of nutrients in medical centers or during mass campaigns. In recent years, crop biofortification is increasingly considered as a complementary approach to address micronutrient deficiencies for difficult-to-reach rural populations who generally have limited access to health facilities and predominantly rely on their own food production for consumption. In this paper, we assess the potential health and economic impacts of rice multi-biofortification. We focus on Nigeria and Ghana, two countries where the importance of rice as a staple food is rapidly increasing and where micro-nutrient deficiencies are widespread. Our analytical framework is based on the Disability-Adjusted Life Years framework. We draw parameter estimates from large-scale household surveys such as the DHS and the LSMS-ISA as well as from previous literature in health and economics. Our findings confirm the existence of a large health burden caused by the inadequate intake of Vitamin A and Zinc among children under five and women in childbearing age, and the inadequate intake of Iron among adults in both Nigeria and Ghana. We also found that, under optimist assumptions about the increase in Vitamin A, Zinc, and Iron contents of biofortified rice varieties and 10 percent adoption by consumers, the total burden of the deficiencies in these nutrients decrease by 93, 612 life years annually in Nigeria and 15, 950 life years annually in Ghana. Subnational analyses show substantial heterogeneity across zones and regions and across sub-populations with children under benefiting the most from increase Vitamin A intake. We also conducted an economic analysis that show that funding multi-biofortification in both Nigeria and Ghana is cost-effective with the countries national gross income increasing by $PPP2.9 billions and $PPP 0.56 billion over the period 2021-2040 in Nigeria and Ghana, respectively. This corresponds to cost per life saved of PPP$58 and PPP$54, respectively.

Keywords: Multi-biofortification, Vitamin A, Zinc, Iron, DALY, Nigeria, Ghana

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1 Introduction

Food insecurity remains an important development challenge for most developing countries, and is particularly acute in sub-Saharan Africa (UNICEF, 2021). The high prevalence of food insecurity in this region has meant that millions of people suffer from inadequate calorie intake. Food insecurity also manifests in the form of malnutrition associated with micronutrient deficiencies; a form of malnutrition dubbed “hidden hunger”. This form of hunger is particularly detrimental to children as well as pregnant and breastfeeding individuals. Micronutrient malnutrition is acute among poor rural households in areas where the diet consists primarily of cereals and starchy food crops with low micronutrient content. In the case of Nigeria, Ezeh et al (2021) document that more than 33 percent of deaths among children aged 0-59 months could be attributed to malnutrition which among others includes dietary deficiency of micronutrients. Several other studies examining the impact of micronutrient deficiency on children in Ghana find similar negative results (Lartey et al. 1999). Micronutrient malnutrition has been shown to affect global health and economic development greatly (Fink et al. 2016, McGovern et al. 2017).

While clinical administration of micronutrients is commonly used for children, those at risk, and those suffering micronutrient deficiency, it is a generally curative approach. Increasingly, biofortification of staple crops that most people consume in a given locality is becoming a preferred pathway to deliver micronutrients to mass populations sustainably. Indeed cassava, a key staple crop in several African countries, has been one such candidate biofortified to deliver micronutrients and early results show impressive results. Studies in Kenya and Nigeria respectively found that children who consumed biofortified cassava had high concentrations of beta carotene which is a precursor of vitamin A (Talsma et al. 2016, Afolami et al. 2021). As a major staple food crop in both Nigeria and Ghana, rice could provide a key vehicle to deliver micronutrients to populations that are vulnerable to micronutrient deficiency.

We conducted an ex-ante assessment of the potential benefits of healthier rice using the Disability-Adjusted Life Years (DALY) framework which has become a standard framework to assess the health gap of diseases in developing countries (Anand and Hanson, 1997, Anand and Hanson, 1998). The DALY framework is an accounting framework that is used to translate the mortality and morbidity risks associated with a disease or health condition into a single index expressed in terms of the number of DALYs lost. To assess the potential health impacts of multi-biofortified rice, we compare the current DALYs lost under the current patterns in rice consumption in Nigeria and Ghana to the potential DALYs lost if a given proportion of the current rice consumption is replaced by rice with increased vitamin A, Zinc, and Iron contents.

There is growing literature on micronutrient malnutrition and the potential impacts of biofortification. Bouis and Saltzman (2017) provide a recent review of this literature. This literature comprises breeding and bioengineering works (see for example Khush et al. 2012, Sharma et al. 2017 among others) that study the technical feasibility and effectiveness of biofortification. It also includes studies on the health and economic impacts of biofortification (Qaim et al. 2007, Meenakshi, 2010, Saltzman, 2013, De Steur et al. 2017). Earlier studies have focused on the impact of a single nutrient biofortification, but in recent years the literature has shifted to assessing the impact of multi-biofortification (Sayre et al. 2011, Goredema-Matongera et al. 2021). Our study contributes to this second generation of biofortification studies by assessing the health impacts of rice multi-biofortification with key micronutrients of iron, zinc and vitamin A among key segments of the population such as infants and women of childbearing age that are typically prone to micronutrient deficiencies in two African countries, Nigeria and Ghana where rice consumption is large and growing rapidly. Most previous studies focused on Asia, most notably the Philippines where biofortified rice is also marketed and China and India which are two of the world's largest rice producers and consumers.

We also make a unique contribution to the literature by explicitly capturing geographic heterogeneity in the analyses. Most previous studies have focused on national estimates treating consumers in each country as homogenous. However, several studies and recent data have shown large geographic heterogeneity in consumption patterns within a country. In Nigeria and Ghana, our two focus countries, the importance of rice in households' diet varies significantly across states. There are differences in rice consumption per capita between rural and urban households. Our analyses were conducted at the subnational level. We captured six zones in Nigeria and ten in Ghana. The choice of this level of analysis was constrained by the level at which the rice consumption data were representative.

The rest of the paper is organized as follows. In Sections 2, we provide a background of the state of crop biofortification in Nigeria and Ghana. Section 3 covers the DALYs framework, data sources on key parameters and assumptions including sub-national disaggregation, modeling of adoption over project timeline and summary statistics. In Section 4, we present the key findings of the study disaggregated by micronutrient and country. The section also includes additional cost effectiveness and sensitivity analysis. The paper is then concluded in Section 5.

2 Background

Although crop biofortification is still not widespread in Africa, in the past decade, Nigeria took considerable steps to embrace biofortification. In 2010, the country together with other partners, set up the *Staple Crop Biofortification Program* to help drive the delivery of biofortified crops to farmers (Ilona et al, 2017, Onuegbu et al, 2017, Birol et al, 2022). Since then, the country has released several varieties of biofortified cassava, maize and orange fleshed sweet potato that farmers are currently cultivating. As one of the leading cassava producers and consumers in the world (Ugwu, 1996, Okwuono, 2021) its biofortification and cultivation provides a tremendous window of opportunity for other staple crops such as rice in the country. While Ghana on the other hand has also rolled out some biofortified crops i.e. sweet potato and maize; the range of these crops is much less than that in Nigeria. Besides, these are not some of the major staple crops either cultivated or consumed in the country. Besides the few biofortified crops already released in Nigeria and Ghana respectively, a lot of efforts are being directed at biofortifying more crops to help deliver micronutrients to households that largely depend on consuming food from their own production.

Several ex-ante analyses have documented the potential nutritional benefits of biofortification of different crops in some selected African countries. Nguema et al; (2011) in their analysis of expected benefits of biofortified cassava in Nigeria and Kenya report that it could lower the burden of iron and Vitamin A deficiency by 3 percent and 6 percent respectively. Fiedler et al. (2013) show that biofortified high-provitamin A and high-iron banana in Uganda could lower the burden of Vitamin A deficiency and IDA by 3-5 percent. Still examining the benefits of high-Provitamin A bananas in Uganda, Kozicka et al. (2021) show that it will lead to a potential reduction of vitamin A deficiency in the country. Lividini and Fiedler (2015) also show that high provitamin A maize in Zambia will potentially contribute to an average additional intake of 12% percent of the Estimated Average Requirement (EAR), which translates into a 3-percentage point reduction in the prevalence of inadequate intake.

The significant nutritional benefits for children and women of childbearing age especially in Nigeria is an important result worth highlighting because these are the segments of the population that have historically suffered the most from micronutrient deficiency (Harika et al. 2017). However, the benefits of biofortified crops have not only been limited directly to improvement of nutritional outcomes in the population. For example, Kolapo and Kolapo (2021) also show that cultivation of biofortified cassava had a positive impact on farm households' cassava yield and income. evidence on the nutritional impact, consumer and farmer acceptance, and cost-effective scalability of biofortified crops.

3 Methodology and data sources

3.1 The data DALYs framework

Micronutrient malnutrition has health consequences in the form of short- and long-term health conditions and can also lead to death. Since the seminal Global Burden Disease study, the Disability-Adjusted Life Years (DALY) framework has become the standard framework to assess the health gap of diseases in developing countries. The DALY framework has also been widely used to assess the burden of micronutrient deficiencies in these countries. It translates the mortality and morbidity risks associated with a disease or health conditions in a single index expressed in terms of the numbers of DALYs lost using the following:

$$DALYs_{lost} = \underbrace{\sum_j T_j\, M_j \left(\frac{1-e^{-rL_j}}{r}\right)}_{Years\ of\ life\ lost\ (YLL)} + \underbrace{\sum_j \sum_i T_j\, I_{ij} D_{ij} \left(\frac{1-e^{-rd_{ij}}}{r}\right)}_{Years\ lived\ with\ disability\ (YLD)}$$

Where T_j is the total number of people in target group j; M_j, the mortality rate associated with the deficiency in target group j; L_i, the average remaining life expectancy for target group j; I_{ij}, the incidence of functional ailment i in target group j; D_{ij}, is the disability weight for functional ailment i in target group j, d_{ij}, the duration of functional ailment i in target group j; and r, the discount rate for future life years.

The DALY formula can be applied to assess the change in health gap due to specific interventions that result in changes of the value of key parameters. In our case, the DALY framework is used to estimate potential health impact multi-biofortification of rice in Nigeria and Ghana that would increase the intake of vitamin A, zinc, and iron and consequently reduces the burden of malnutrition due to the deficiency of these key micronutrient in specific target populations. We do so by comparing the DALY lost in the status quo to the DALY lost with the adoption of multi-biofortified rice.

3.2 Data sources on key parameters and assumptions

The application of the DALY framework to assess the potential impact of multi-biofortification of rice relies on key parameters. We draw from several data sources to obtain the values of these parameters and make assumptions informed by the literature and expert knowledge to fill the data gap when reliable data sources are unavailable. The section discusses the sources underlying the key parameters used in the analysis and the assumptions underlying the estimation of benchmark values and values under the multi-biofortification of rice.

Based on a review of the health and nutrition literature, we determine the target population at higher risk of deficiency of vitamin A, zinc, iron the three key micronutrients considered in the analysis. Vitamin A deficiency is more severe and more consequential among children under five and pregnant women. When not treated, it can lead to episodes of measles, sometimes with complications. It can also lead to various vision problems such as xerophthalmia and scarring and over time to night blindness or complete blindness. Prolonged vitamin A deficiency has also been shown to be a leading cause of child death. Acute zinc deficiencies cause diarrhea and pneumonia among children and can also lead to death. Iron deficiencies are leading causes of physical and mental impairments in children and adults. For pregnant women, prolonged acute iron deficiencies lead to fatal pregnancies and sometimes stillbirths and perinatal mortality.

We draw our estimates of the size of the population in each target group from the Nigeria National Bureau of Statistics and the Ghana Statistical Service. We also gather published estimates of the prevalence of various conditions related to vitamin A deficiency, zinc deficiency, and iron deficiency by country and age group. These estimates come from various sources, including the Demographic and Health Surveys (DHS), the Global Burden of Disease (GBD) estimates from the Institute for Health Metrics & Evaluation (IHME), and other relevant literature with the most recent data available. Incidence rates, which are key parameters in the DALY formula, are derived from the prevalence rate using the formulas from DeSteur et al. (2012). For temporary conditions such as diarrhea and measles, we use the formula: 'prevalence rate' divided by 'duration of the disease.' For permanent conditions such as blindness and corneal scarring, we use the formula: 'prevalence rate' multiplied by 'size 1st age cohort' divided by 'size target group.' Also following DeSteur et al. (2012), we use standard values of other parameters related to disability weights, disease durations, and discount rates.

We calculate daily per capita rice consumption for the different age groups in three steps. First, we calculate the daily household per capita consumption using the LSMS-ISA for Nigeria and the Ghana socioeconomic survey (GSS) for Ghana. We include both rice consumption that comes from household production and market purchase. To obtain the daily rice consumption by the different age groups, we multiply the daily household per capita consumption by the OECD-modified adult equivalent scales as proposed by Hagenaars et al. (1994) which assigns a weight of 1 for the first adult in a household, 0.5 for each additional adult and 0.3 for each child. This approach obviously has some weaknesses, not least the inability for example to separate the consumption between different age categories of children (1-4 vs 5–14-year-olds) since they have the same scale of 0.3. Additionally, it also does not allow us to segregate consumption between men and women both overall and within age groups.

Parameters for healthier rice nutrient uptake were informed by research scientists at the International Rice Research Institute in Los Baños, Philippines. These parameters include estimates on improved micronutrient content, post-harvest losses, and bioavailability of multi-biofortified rice. Though informed by experts, these nutrient uptake estimates are still largely based on field and efficacy trials in populations other than Nigeria and Ghana. Accordingly, our team designed two separate scenarios–one pessimistic and one optimistic–as a preliminary sensitivity analysis to parameter uncertainty. We describe a more robust sensitivity analysis in Section 5.4 of this paper. Finally, cost estimates for program field trials, seed system support, social marketing, and maintenance breeding were informed by previous agricultural development and biofortification projects.

3.3 Methodology on sub-national disaggregation

Our model provides sub-national estimates for both Nigeria and Ghana. To achieve this, we used different sub-national designations for each country. For Nigeria, we utilized the six geopolitical zones recognized by the Federal Republic of Nigeria (see Table 1A in the Appendix). For Ghana, we used the 10 geopolitical regions recognized by the Republic of Ghana (see Table 2A in the Appendix). Notably, the Republic of Ghana split its 10 regions into 16 regions in 2018. However, since most sub-national population and consumption data were available for the 10 former regional designations, we based our analysis on these.

We input heterogeneous parameter estimates by zone in Nigeria and region in Ghana whenever possible. In instances where zonal or regional data were not available, we relied on national estimates. Specifically, for the Nigeria analysis, we incorporated heterogeneous estimates for population, life expectancy, consumption, and some disease prevalence data, wherever available. For the Ghana analysis, we integrated heterogeneous estimates for population, consumption, and some disease prevalence data, but we lacked life expectancy estimates at the sub-national level. Overall, our approach aimed to produce accurate and reliable sub-national estimates that capture the inherent variations in different geographic regions.

3.4 Modeling adoption over project timeline

To estimate the cost effectiveness of introducing multi-biofortified rice in Nigeria, we model the costs and benefits over twenty years with underlying assumptions about multi-biofortified rice adoption. For the pessimistic and optimistic scenarios, we assume a maximum adoption of 10 percent and 20 percent respectively, twenty years after introduction. We estimate adoption in year (t) with the following formula:

$$Adoption_t = \frac{A_{max}}{1 + \left(\frac{A_{max}}{A_{min}} - 1\right) \times e^{-\gamma(t-T)}}$$

Where A_{max} denotes maximum adoption of 10 percent (pessimistic) or 20 percent (optimistic), A_{min} denotes minimum adoption of 1 percent or 2 percent, γ denotes our chosen adoption acceleration factor of 0.5, and T represents our chosen time of adoption acceleration in 2028. Figure 1 demonstrates the adoption curves under both scenarios.

Figure 1. Model adoption curve for Nigeria and Ghana

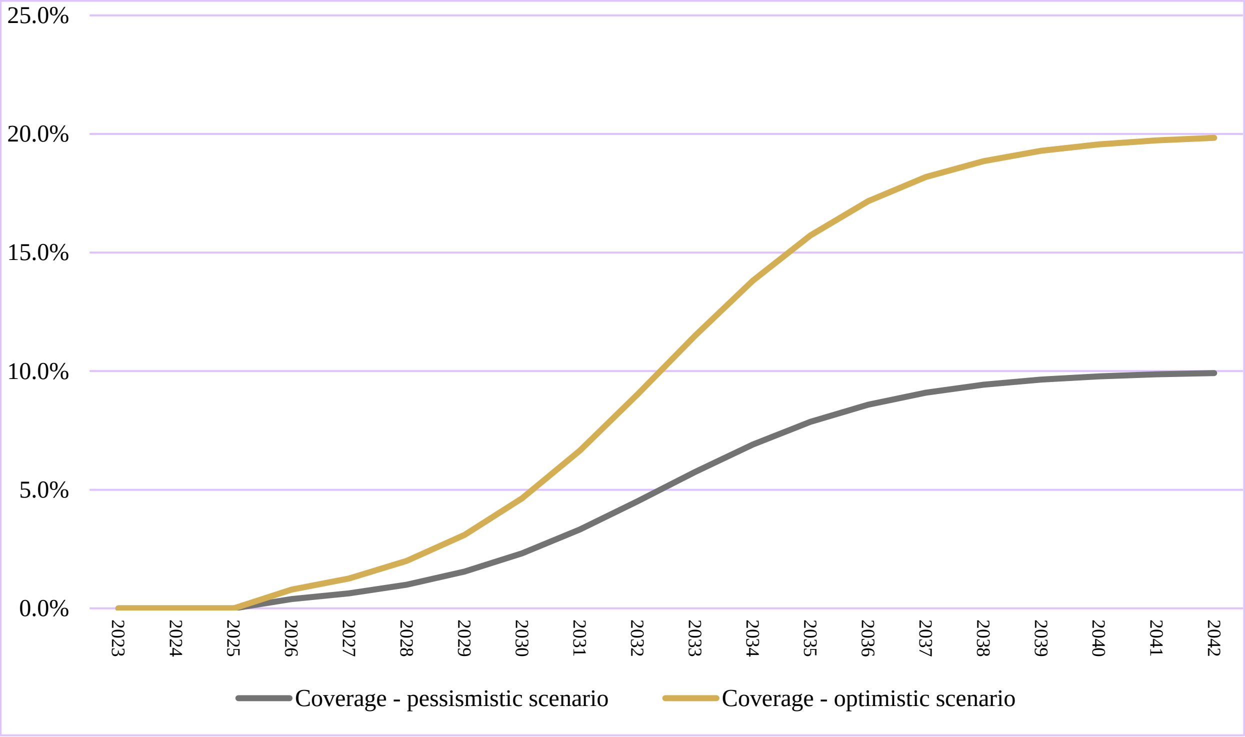


Figure 1 shows the pessimistic and optimistic adoption curves representing a scaled adoption of multi-biofortified rice over twenty years in both Nigeria and Ghana. In the pessimistic scenario, we are assuming that no adoption of multi-biofortified occurs in the first few years after introduction. After twenty years, we assume a maximum adoption of 10 percent.

3.5 Summary statistics

Table 1a and 1b respectively summarize the daily rice consumption by the different age groups in the populations in Nigeria and Ghana. The results not only reveal interesting differences between the two countries but also within each country across different regions. First, the results show that across different age categories, daily rice consumption is much lower Nigeria (Table 1a) than in Ghana (Table 1b). Within Nigeria, there is also an interesting rice consumption divide between the north and south of the country. Basically, in predominantly arid north with less favorable ecology for rice cultivation, consumption is considerably lower than in the south of the country. Besides agroecological differences between the two regions, this trend is also consistent with differences between the north and south in terms of welfare indicators such as poverty.

Table 1a: Nigeria daily rice consumption, grams/person/day

	National	North Central	North East	North West	South East	South South	South West
Women of CBA	88.84	71.52	52.76	50.42	164.91	129.14	74.66
Children 1- 4 yrs	34.54	30.26	23.32	21.99	67.61	55.44	29.38
Children 5-14 yrs	36.91	30.69	23.00	21.55	69.75	57.26	28.74
Women 15+	97.35	75.81	53.76	51.65	179.76	134.80	84.10
Men 15+	94.05	74.40	54.94	52.19	169.77	134.19	84.94

Source: based on Nigeria LSMS-ISA 2010/2011, 2012/2013, 2015/2016 and 2018/2019 data.

Table 1b: Ghana daily rice consumption, grams/person/day

	National	Ashanti	Brong-Ahafo	Central	Eastern	Greater Accra	Northern
Women of CBA	187.0	290.8	169.8	97.9	84.0	187.0	194.4
Children 1- 4 yrs	78.8	94.4	62.8	30.6	41.9	78.8	89.5
Children 5-14 yrs	81.8	113.7	64.4	38.2	28.6	81.8	87.0
Women 15+	192.6	293.7	167.0	85.6	84.0	192.6	191.4
Men 15+	191.4	246.2	193.2	38.9	74.7	191.4	200.7

Source: based on Ghana Living Standards Survey 2017 data.

Table 1b: continued

	Upper East	Upper West	Volta	Western
Women of CBA	181.1	195.6	153.8	189.5
Children 1- 4 yrs	70.2	87.0	57.1	91.6
Children 5-14 yrs	81.4	83.9	64.9	58.5
Women 15+	195.3	194.7	167.3	176.8
Men 15+	193.7	185.4	162.1	210.0

Source: based on Ghana Living Standards Survey 2017 data.

4 Findings

4.1 Current burden of deficiencies

Our model estimates that the burden of deficiencies in vitamin A, zinc, and iron in Nigeria is large with over 7.9 million DALYs lost annually, or an average of 0.04 life-years (equivalent of 15 days) lost per person every year. For Ghana, the current burden of micronutrient deficiencies is 590,000 DALYs lost annually, or an average of 0.02 life-years (equivalent of 7 days) lost per person every year. Figure 2 summarizes the current burden of micronutrient deficiencies in Nigeria and Ghana by deficiency type as well as non-fatal and fatal outcomes. Between the three micronutrient deficiencies, iron deficiency contributes the most to the current annual burden of DALYs in both Nigeria and Ghana.

Figure 2a. Current annual burden of micronutrient deficiencies by micronutrient in Nigeria

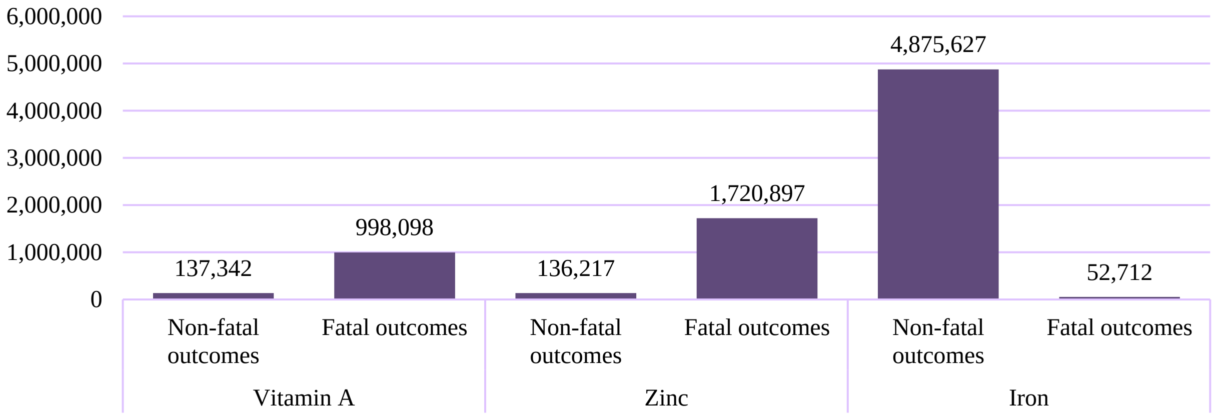
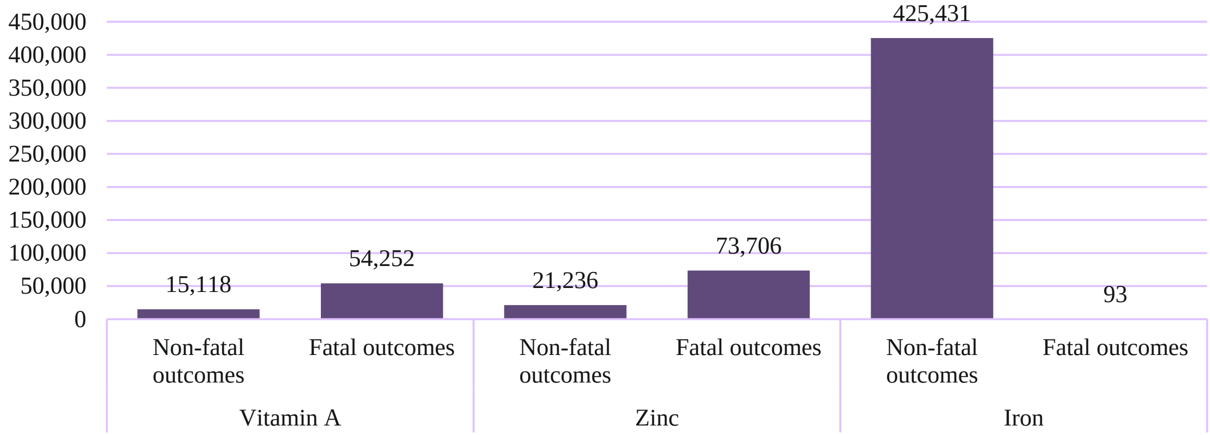


Figure 2b. Current annual burden of micronutrient deficiencies by micronutrient in Ghana



Figures 2a and 2b respectively show the DALYs lost by deficiency, disaggregated by non-fatal and fatal outcomes in Nigeria and Ghana. For Nigeria (Figure 2a), we estimate that the current annual burden attributable to vitamin A deficiency is 1.1 million DALYs, with 137,000 years lost due to non-fatal outcomes and 998,000 years lost due to fatal outcomes (primarily child mortality).

Micronutrient deficiencies have been shown to have differential impacts on different sub-populations. In Figure 3, we disaggregate the total current burdens of the three micronutrients by age group and gender. In both Nigeria and Ghana, children aged 1-4 bear the largest burden with 4.3 million and 338,000 DALYs lost annually respectively. These estimates are influenced by the larger remaining life expectancy of children and the disproportionate DALYs lost due to fatal outcomes from micronutrient deficiencies. While in Nigeria, the second most affected age group consists of children aged 5-14, in Ghana, women aged 15+ bear the second highest burden. In both geographies, men 15+ are affected significantly less by micronutrient deficiencies.

Figure 3a. Current annual burden of micronutrient deficiencies by age group and gender in Nigeria.

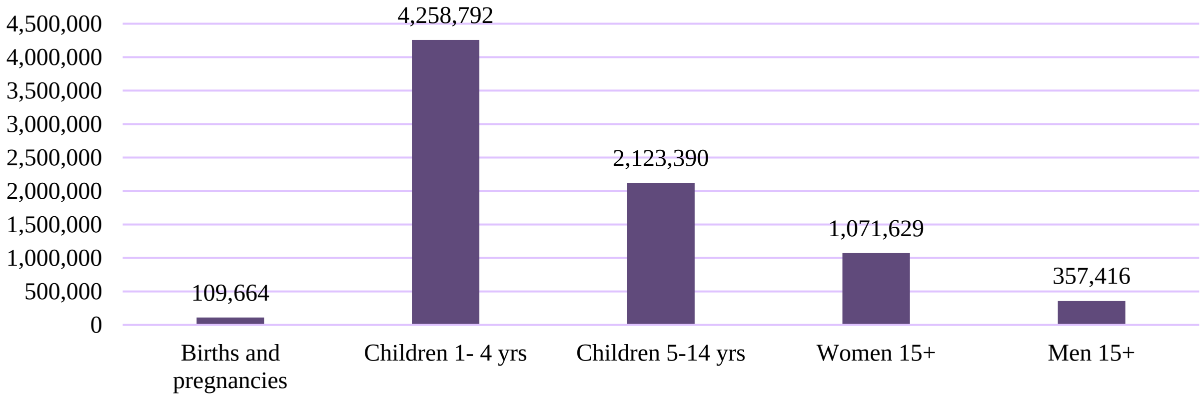
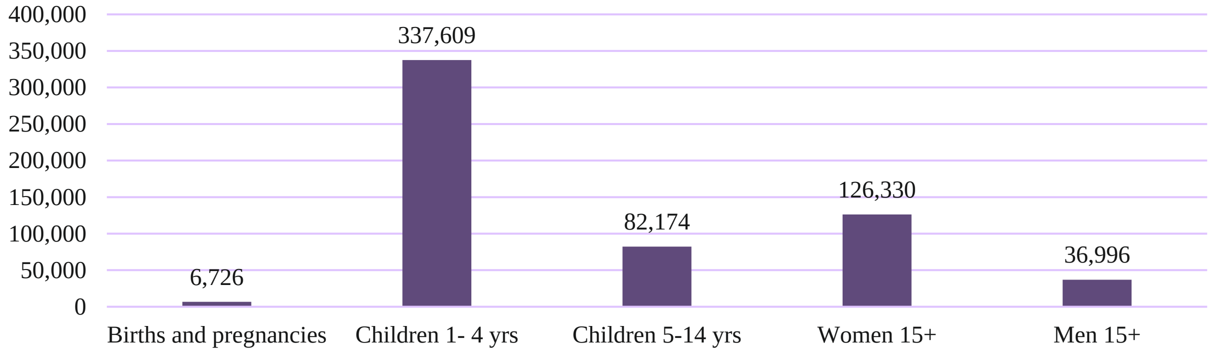


Figure 3b. Current annual burden of micronutrient deficiencies by age group and gender in Ghana.



Figures 3a and 3b respectively show the DALYs lost by deficiency, disaggregated by age group and gender in Nigeria and Ghana. In Ghana, we estimate that children aged 1-4 bear the largest current burden of DALYs at 338,000.

Finally, the analysis also reveals variations in DALYs lost at the sub-national level. Figure 4 summarizes sub-national DALY burden for Nigeria and Ghana. In Nigeria, the zones with highest burden are the North West with 3.2 million followed by North East with 1.3 million, and the North Central with 1.1 million. In Ghana, the regions with the highest burden are the Ashanti region with 100,000 followed by Northern region with 87,000, and the Greater Accra region with 79,000.

Figure 4a. Current annual burden of micronutrient deficiencies by zone or region in Nigeria

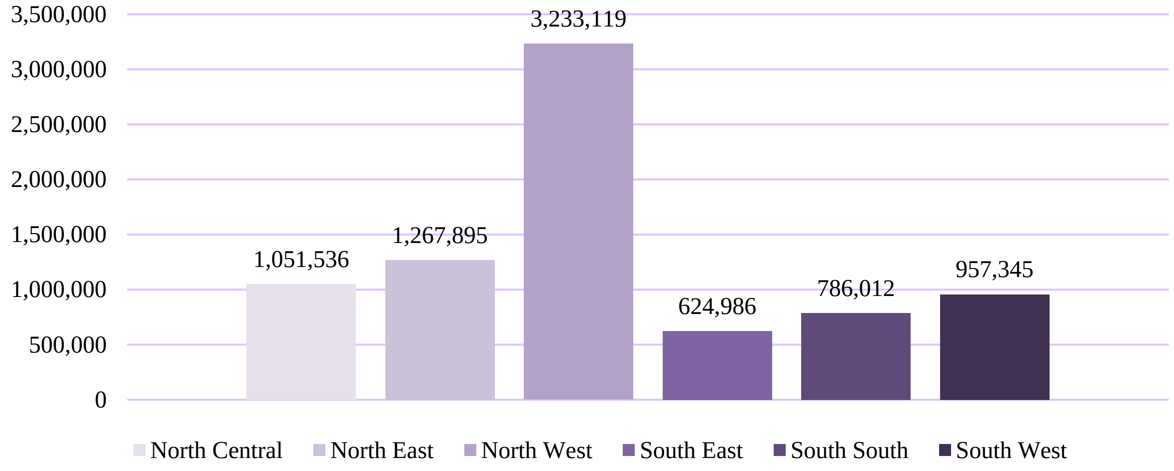
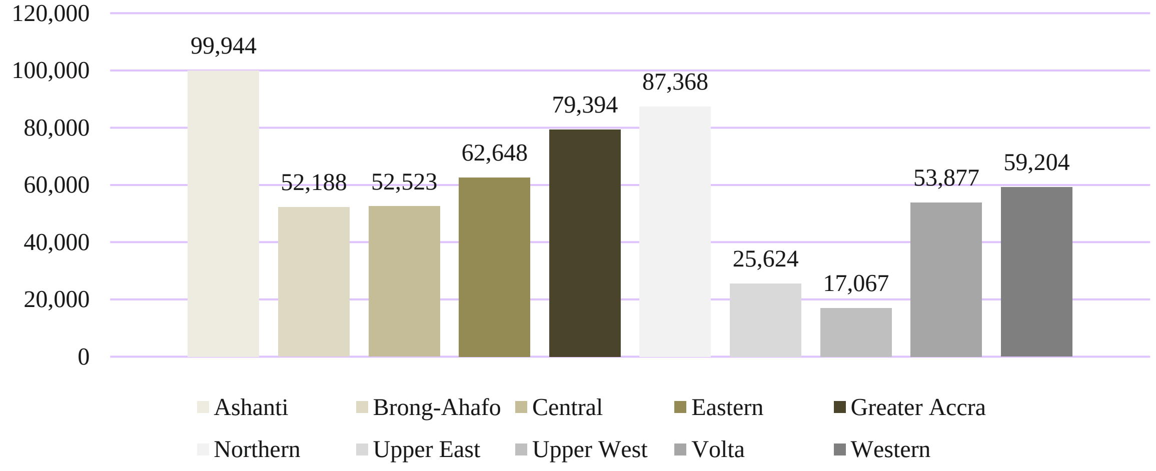


Figure 4b. Current annual burden of micronutrient deficiencies by zone or region in Ghana



Figures 4a and 4b respectively show the DALYs lost, disaggregated at the sub-national level in Nigeria and Ghana. In the North West zone of Nigeria, we estimate the highest current burden of micronutrient deficiency with 3.3 million DALYs lost annually.

4.2 Estimating impacts of multi-biofortified rice

Next, we assess the potential reduction in DALYs lost if rice consumption patterns remain constant, but the nutrient content is improved with multi-biofortification. We begin with pessimistic assumptions about nutrient availability in multi-biofortified rice as soil content, storage, and preparation can impact the final nutrient availability of consumed rice. Under pessimistic assumptions and an adoption rate of 10 percent, we estimate that multi-biofortified rice would reduce the burden of micronutrient deficiencies by 94,000 DALYs annually in Nigeria and 16,000 DALYs annually in Ghana. Table 2 summarizes the DALY burden saved disaggregated by micronutrient, age, and gender for both Nigeria and Ghana. Whereas Nigeria exhibits a higher burden saved overall, Ghana exhibits a higher burden saved as a percentage of the current DALY burden by micronutrient.

Table 2a. Annual burden saved with pessimistic assumptions and 10 percent adoption in Nigeria

	Vitamin A	**Zinc**	**Iron**	**All**
Births and pregnancies	2,649	0	201	2,850
Children 1- 4 yrs	37,551	30,518	7,066	75,136
Children 5-14 yrs	0	0	8,299	8,299
Women 15+	0	0	4,390	4,390
Men 15+	0	0	2,937	2,937
Total	**40,200**	**30,518**	**22,893**	**93,612**
Current burden	1,135,440	1,857,113	4,928,339	7,920,893

Percent reduction of current burden	*3.54%*	*1.64%*	*0.46%*	*1.18%*

Table 2b. Annual burden saved with pessimistic assumptions and 10 percent adoption in Ghana

	Vitamin A	**Zinc**	**Iron**	**All**
Births and pregnancies	440	-	1	441
Children 1- 4 yrs	3,333	7,034	2,520	12,888
Children 5-14 yrs	-	-	600	600
Women 15+	-	-	928	928
Men 15+	-	-	1,093	1,093
Total	**3,774**	**7,034**	**5,142**	**15,950**
Current annual burden	69,370	94,942	425,525	589,836
Percent reduction of current burden	*5.44%*	*7.41%*	*1.21%*	*2.70%*

Tables 2a and 2b respectively show the Annual DALYs saved as a result of multi-biofortification with pessimistic assumptions and 10 percent adoption disaggregated by micronutrient, age, and gender. Under pessimistic assumptions and an adoption rate of 10 percent, we estimate that multi-biofortified rice would reduce the burden of micronutrient deficiencies by 94,000 DALYs in Nigeria and 16,000 DALYs in Ghana *annually*. These amounts represent reductions in the current annual burden of micronutrient deficiencies by 1.18 percent and 2.7 percent respectively.

Due to underlying differences in disease burden, rice consumption, and population at the sub-national level in both Nigeria and Ghana, we disaggregate our results by zone and region. Figure 4 summarizes DALYs saved as a result of biofortification at the sub-national level in Nigeria and Ghana. For Nigeria, our analysis by zone shows that multi-biofortification can save the most DALYs annually in the North West with 40,000, followed by the North East with 13,000, and South East with 11,000. For Ghana, our analysis by zone shows that multi-biofortification can save the most DALYs annually in the Ashanti region with 3,800 DALYs, followed by the Northern region with 3,200, and the Greater Accra region with 2,200.

Figure 4a. Percent reduction in DALYs with pessimistic assumptions and 10 percent adoption in Nigeria

Zone	Current burden (DALYs lost)	Burden reduction (DALYs saved)	Percent Reduction
North Central	1,051,536	10,870	1.03%
North East	1,267,895	13,259	1.05%
North West	3,233,119	39,907	1.23%
South East	624,986	11,934	1.91%
South South	786,012	10,430	1.33%
South West	957,345	7,212	0.75%
Nigeria	**7,920,893**	**93,612**	**1.18%**

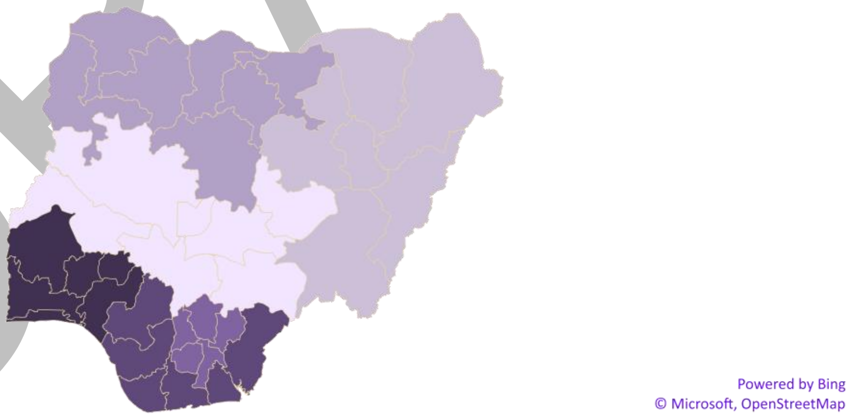


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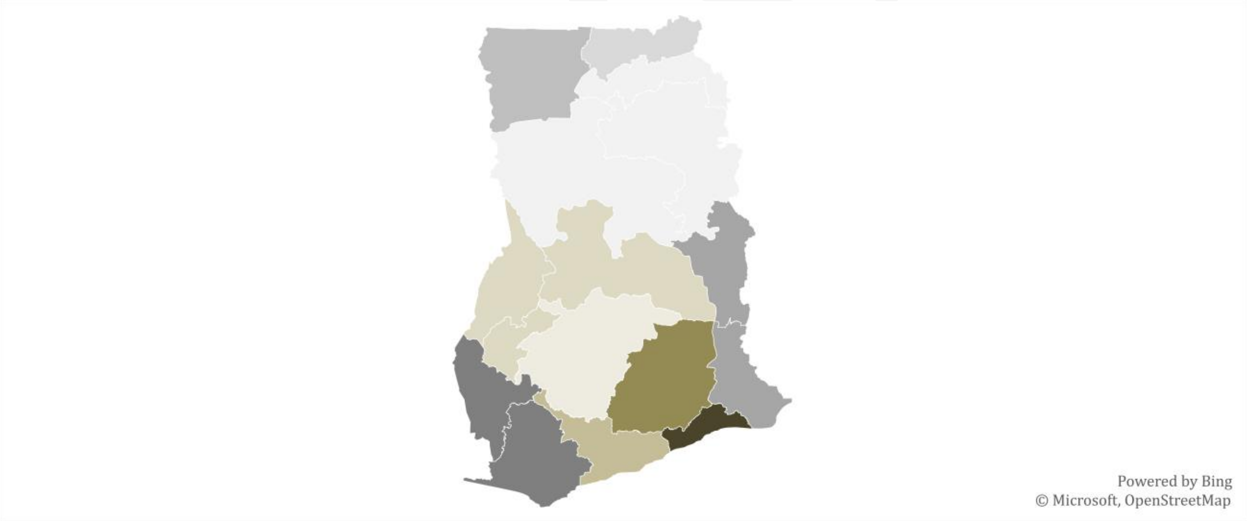
Figure 4b. Percent reduction in DALYs with pessimistic assumptions and 10 percent adoption in Ghana

Region	Current burden (DALYs lost)	Burden reduction (DALYs saved)	Percent Reduction
Ashanti	99,944	3,832	3.83%
Brong-Ahafo	52,188	1,155	2.21%
Central	52,523	504	0.96%
Eastern	62,648	804	1.28%
Greater Accra	79,394	2,269	2.86%
Northern	87,368	3,205	3.67%
Upper East	25,624	708	2.76%
Upper West	17,067	548	3.21%
Volta	53,877	960	1.78%
Western	59,204	1,964	3.32%
Ghana	**589,838**	**15,950**	**2.70%**



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4.3 Cost-effectiveness analysis

We estimate the cost-effectiveness of introducing multi-biofortified rice to Nigeria and Ghana by modeling known costs and benefits over twenty years, 2021-2040. Cost estimates stem from similar program spending on field trials, seed system support, social marketing, and maintenance breeding and are adjusted to $PPP. Our model assumes that spending on field trials and seed system support occur in the early years of introduction whereas spending on social marketing and maintenance breeding scale with adoption level over time. Currently, our included costs are non-exhaustive, but we discuss how these omissions would impact the analysis later in this section. In particular, our analysis omits two costs borne by farmers who adopt multi-biofortified seeds: 1) an additional cost of purchasing multi-biofortified seed versus a traditional seed and 2) adoption costs such as learning and changed farming practices.

In the Appendix, Table A3a and A3b summarize the costs and benefits over twenty years in the pessimistic scenarios for both Nigeria and Ghana. Given the smaller geographic size and population size of Ghana compared to Nigeria, we use smaller cost estimates in $PPP regarding field trials, seed system support, social marketing, and maintenance breeding in accordance with programs of similar size. We monetize the benefits of DALYs saved by multiplying DALYs saved by Nigeria's per-capita gross national income (GNI) in $PPP. As DALYs saved per year are contingent on scaled adoption, we scale DALYs saved to our adoption curve under pessimistic assumptions with a maximum adoption of 10 percent. Using a chosen discount rate of 3 percent, we estimate that the twenty-year net present value (NPV) of the introducing multi-biofortified rice to Nigeria and Ghana under pessimistic assumptions are $2.9 billion and $556 million respectively. Table 3 summarizes key economic estimates of the model including internal rate of return, benefit cost ratio, and cost per DALY saved. In the pessimistic scenario, we estimate the cost per DALY saved to be $57.98 in Nigeria and $54.70 in Ghana.

Although we assume that farmers do not incur any additional costs in adopting multi-biofortified rice, we conducted a simple back-of-the-envelope calculation to estimate the hypothetical additional adoption cost that a farmer would need to incur to shift the net present value of the project from positive to negative. Using a household survey dataset, we estimate 8 percent of individuals in Nigeria reside in rice-producing households. While comparable estimates for Ghana are not available, we assume roughly the same percentage of Ghanaians partake in rice production. Accordingly, with a 10 percent adoption rate among all farmers in each country, the net present value of the projects would only become negative if farmers incurred an additional average cost of $1,807 in Nigeria and $2,247 in Ghana. When comparing these amounts to annual per capita GNI ($PPP) within each country (Table 3), we presume the true costs of adoption will fall far below each estimate. Further, we presume adoption costs would need to be even higher to generate a negative NPV as our calculation valued all adoption costs in the present year instead of the future years. We plan to expand our analysis to include adoption costs in further renditions of this paper.

Table 3a. Summary of key economic parameters (2021-2040) in Nigeria

	Pessimistic scenario	**Optimistic scenario**
Total DALYs saved	941,370	3,930,935
with Vitamin A	404,260	1,925,678
with Zinc	306,896	1,030,840
with Iron	230,214	974,417
Present value of DALYs saved ($ millions)	$2,963.04	$12,372.96
Present value of cost ($ millions)	$29.80	$29.80
Net present value ($ millions)	$2,908.47	$12,372.96
Benefit Cost Ratio	54	227
Cost per DALY saved ($/DALY saved)	$57.98	$13.88
Internal Rate of Return	41%	69%
Additional cost/farmer for net negative	$1,807.53	$3,827.77
GNI ($PPP)	$4,716.01	$4,716.01

Table 3b. Summary of key economic parameters (2021-2040) in Ghana

	Pessimistic scenario	**Optimistic scenario**
Total DALYs saved	160,390	504,904
with Vitamin A	37,948	137,373
with Zinc	70,736	161,030
with Iron	51,706	206,501
Present value of DALYs saved ($PPP millions)	$565.17	$1,779.15
Present value of cost ($PPP millions)	$8.77	$8.77
Net present value ($PPP millions)	$556.40	$1,770.38
Benefit Cost Ratio	64	203
Cost per DALY saved ($PPP/DALY saved)	$54.70	$17.38
Internal Rate of Return	50%	76%
Additional cost/farmer for net negative	$2,246.80	$3,574.48
GNI ($PPP)	$5,279.60	$5,279.60

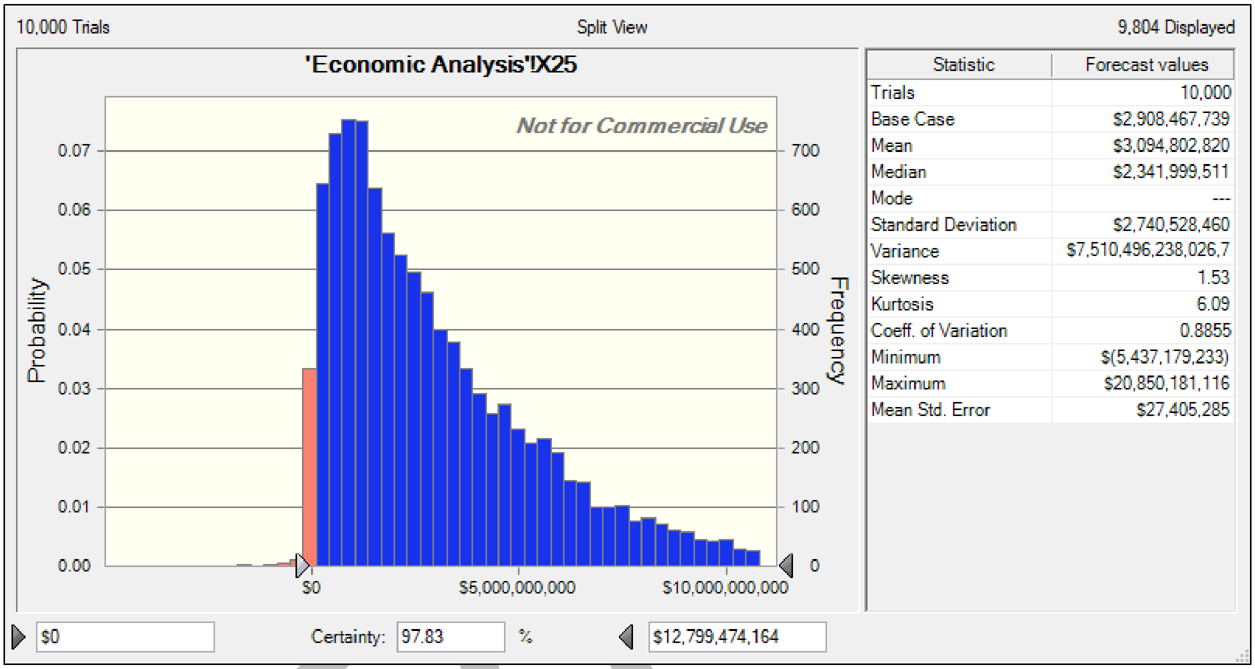
Note. Benefits, costs, and economic parameters over twenty years, 2021-2040 with a chosen discount rate of 3 percent.

4.4 Sensitivity analysis

We utilized Oracle Crystal Ball to conduct a probabilistic Monte Carlo sensitivity analysis that accounts for uncertainties across a range of variables, including disease, rice consumption, nutrient availability, cost, and adoption curve parameters. We drew data from various sources that provided existing confidence intervals or upper and lower estimates of the parameter, which we used to inform the simulation. For parameters without available confidence intervals, we conducted extensive literature searches to identify multiple point estimates from which we could build a uniform distribution. When multiple point estimates or confidence intervals were unavailable, we developed a uniform distribution with upper and lower bound values set at 10 percent above and below the given point estimate. In Table A4 of the Appendix, we provide a summary of each parameter entered into the simulation, including point estimates, upper and lower bound values, distributions, and notes for Nigeria. These assumptions and distribution decisions were nearly identical to those made with Ghana given the similarity of data sources and gaps. As new data and estimates emerge, we plan to enhance the sensitivity analysis with additional inputs.

The mean simulated NPV of introducing multi-biofortified rice to Nigeria and Ghana are $3.1 billion and $418 million under pessimistic assumptions and a maximum adoption rate of 10 percent after twenty years. 97.83 percent of the simulated NPVs for Nigeria are between $0 and $21.0 billion. 98.06 percent of the simulated NPVs for Ghana are between $0 and $23.5 billion. Figure 5 shows the frequency of the simulated net present values. For Nigeria, the largest contributors to variance are maximum coverage rate (38.4 percent), Gamma (28.6 percent), and minimum coverage rate (10.3 percent). For Ghana, the largest contributors to variance in the simulation are time when adoption accelerates (-27.0 percent), discount rate (-22.3), maximum coverage rate (18.4 percent), Gamma (15.1 percent), and minimum coverage rate (11.6 percent). Due to significant uncertainty around coverage, rate of adoption, and discount rate, it makes sense that these variables are the largest contributors to variance within the simulated NPVs. Refer back to Section 4.3 for a description of these model variables and their relative uncertainties.

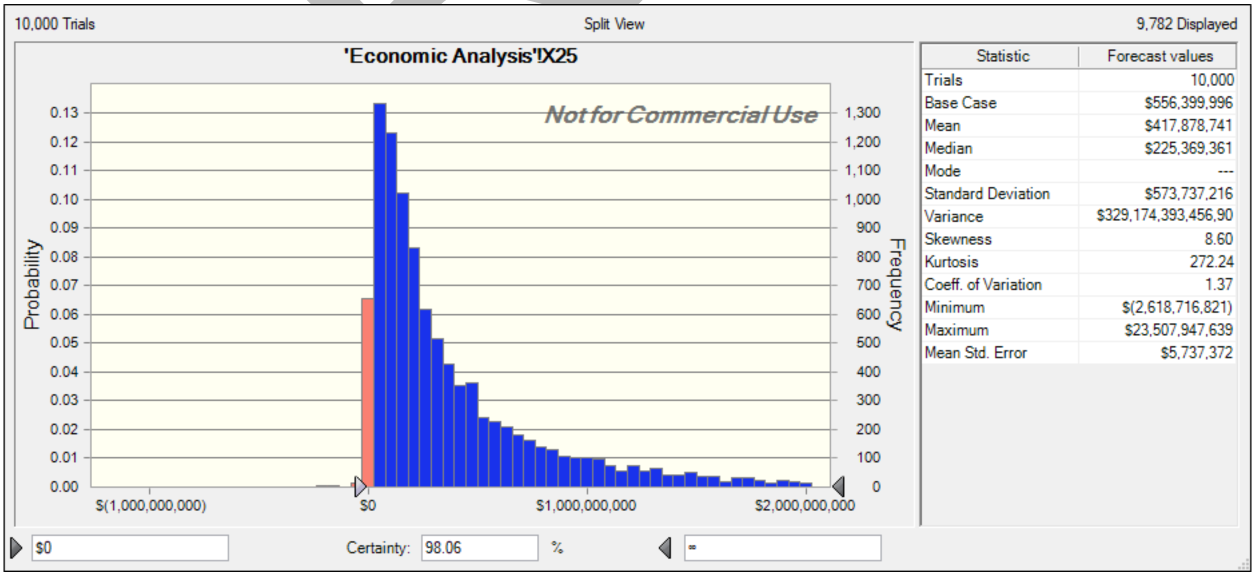
Figure 5a. Simulated net present values with 10,000 trials, Nigeria



Statistic	Forecast values
Trials	10,000
Base Case	$2,908,467,739
Mean	$3,094,802,820
Median	$2,341,999,511
Mode	---
Standard Deviation	$2,740,528,460
Variance	$7,510,496,238,026,7
Skewness	1.53
Kurtosis	6.09
Coeff. of Variation	0.8855
Minimum	$(5,437,179,233)
Maximum	$20,850,181,116
Mean Std. Error	$27,405,285

$0 Certainty: 97.83 % $12,799,474,164

Figure 5b. Simulated net present values with 10,000 trials, Ghana



Statistic	Forecast values
Trials	10,000
Base Case	$556,399,996
Mean	$417,878,741
Median	$225,369,361
Mode	---
Standard Deviation	$573,737,216
Variance	$329,174,393,456,90
Skewness	8.60
Kurtosis	272.24
Coeff. of Variation	1.37
Minimum	$(2,618,716,821)
Maximum	$23,507,947,639
Mean Std. Error	$5,737,372

$0 Certainty: 98.06 % ∞

Note. Figure 5 displays the net present value of introducing multi-biofortified rice to Nigeria and Ghana simulated over 10,000 trials**.** 97.83 percent of the simulated net present values in Nigeria were greater than zero.

5 Conclusion

In many low- and middle-income countries, deficiencies of key micronutrients such as Vitamin A, Zinc, and Iron are endemic and have been shown to have detrimental impacts on economic development. Existing efforts to address these deficiencies through industrial fortification of processed food and clinical administration of nutrient supplements in medical centers or during mass campaigns have still left out many hard-to-reach populations especially in rural areas. In recent years, crop biofortification is being increasingly considered as a complementary approach to address micronutrient deficiencies for difficult-to-reach rural populations who generally have limited access to health facilities and predominantly rely on their own food production for consumption.

Drawing on parameter estimates from several sources, we assess the potential health and economic impacts of rice multi-biofortification in Nigeria and Ghana. Our results show that under an optimist scenario of 10 percent adoption of biofortified rice, the total burden of Vitamin A, Zinc, and Iron deficiencies in the population would decrease by 93, 612 and 15, 950 life years annually in Nigeria and Ghana respectively. Further economic analysis shows that funding multi-biofortification in both Nigeria and Ghana would be cost-effective with the countries national gross income increasing by $PPP2.9 billions and $PPP 0.56 billion over the period 2021-2040 in Nigeria and Ghana, respectively. These results suggest that multi-biofortification rice in Nigeria and Ghana would produce large health and economic benefits and it would be cost-effective.

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Appendix

Table A1. Geopolitical zones, Nigeria

	Geopolitical Zone	States
Zone 1	North Central	Benue, Kogi, Kwara, Nasarawa, Niger, Plateau, FCT Abuja
Zone 2	North East	Adamawa, Bauchi, Borno, Gombe, Taraba, Yobe
Zone 3	North West	Jigawa, Kaduna, Kano, Katsina, Kebbi, Sokoto, Zamfara
Zone 4	South East	Abia, Anambra, Ebonyi, Enugu, Imo
Zone 5	South South	Akwa Ibom, Bayelsa, Cross River, Delta, Edo, Rivers
Zone 6	South West	Ekiti, Lagos, Ogun, Ondo, Osun, Oyo

Table A2. Regions, Ghana

	Regions in Analysis	New Regional Designations
Region 1	Ashanti	
Region 2	Brong-Ahafo	Bono, Bono East, Ahafo
Region 3	Central	
Region 4	Eastern	
Region 5	Greater Accra	
Region 6	Northern	Northern, Savannah, North East
Region 7	Upper East	
Region 8	Upper West	
Region 9	Volta	Volta, Oti
Region 10	Western	Western, Western North

Table A3a. Benefits and costs over twenty years, Nigeria

Year	Costs						Adoption	Discounted monetary value of DALYs saved				Discounted net benefit
	Field trials	Seed system support	Social marketing	Maintenance breeding	Total cost	Discounted total cost		Vitamin A	Zinc	Iron	All	All
0	$5,348,667	$0	$0	$0	$5,348,667	$5,348,667	0%	$0	$0	$0	$0	-$5,348,667.34
1	$5,348,667	$0	$0	$0	$5,348,667	$5,192,881	0%	$0	$0	$0	$0	-$5,192,880.91
2	$5,348,667	$2,139,467	$1,069,733	$534,867	$9,092,734	$8,570,774	0%	$0	$0	$0	$0	-$8,570,774.33
3	$0	$2,139,467	$1,093,296	$558,429	$3,791,192	$3,469,477	0%	$6,813,316	$5,172,357	$3,879,972	$15,865,645	$12,396,167.63
4	$0	$2,139,467	$1,107,616	$572,749	$3,819,832	$3,393,871	1%	$10,635,141	$8,073,712	$6,056,383	$24,765,236	$21,371,364.54
5	$0	$2,139,467	$1,129,733	$594,867	$3,864,067	$3,333,178	1%	$16,353,843	$12,415,090	$9,313,006	$38,081,939	$34,748,760.97
6	$0	$2,139,467	$1,162,630	$627,764	$3,929,861	$3,291,197	2%	$24,582,859	$18,662,182	$13,999,175	$57,244,216	$53,953,019.48
7	$0	$0	$1,208,915	$674,048	$1,882,963	$1,531,022	2%	$35,758,223	$27,146,007	$20,363,199	$83,267,428	$81,736,406.32
8	$0	$0	$1,269,190	$734,323	$2,003,514	$1,581,592	3%	$49,751,431	$37,769,010	$28,331,896	$115,852,337	$114,270,744.51
9	$0	$0	$1,340,245	$805,379	$2,145,624	$1,644,442	5%	$65,509,752	$49,732,006	$37,305,771	$152,547,530	$150,903,087.53
10	$0	$0	$1,414,806	$879,939	$2,294,745	$1,707,506	6%	$81,132,119	$61,591,793	$46,202,225	$188,926,137	$187,218,631.51
11	$0	$0	$1,484,074	$949,207	$2,433,282	$1,757,854	7%	$94,580,770	$71,801,393	$53,860,814	$220,242,977	$218,485,122.11
12	$0	$0	$1,541,514	$1,006,648	$2,548,162	$1,787,230	8%	$104,555,884	$79,374,043	$59,541,332	$243,471,260	$241,684,030.52
13	$0	$0	$1,584,825	$1,049,959	$2,634,784	$1,794,160	9%	$110,829,527	$84,136,706	$63,113,977	$258,080,210	$256,286,049.93
14	$0	$0	$1,615,197	$1,080,331	$2,695,528	$1,782,062	9%	$113,946,145	$86,502,700	$64,888,795	$265,337,640	$263,555,578.29
15	$0	$0	$1,635,429	$1,100,562	$2,735,991	$1,756,128	9%	$114,730,519	$87,098,161	$65,335,471	$267,164,151	$265,408,022.98
16	$0	$0	$1,648,448	$1,113,581	$2,762,029	$1,721,205	10%	$113,952,368	$86,507,424	$64,892,338	$265,352,130	$263,630,924.91
17	$0	$0	$1,656,640	$1,121,774	$2,778,414	$1,680,986	10%	$112,199,533	$85,176,752	$63,894,153	$261,270,438	$259,589,451.68
18	$0	$0	$1,661,723	$1,126,857	$2,788,580	$1,637,997	10%	$109,875,002	$83,412,074	$62,570,405	$255,857,480	$254,219,483.27
19	$0	$0	$1,664,849	$1,129,983	$2,794,832	$1,593,854	10%	$107,238,074	$81,410,239	$61,068,756	$249,717,069	$248,123,214.97
Total	**$16,046,002**	**$10,697,335**	**$25,288,866**	**$15,661,265**	**$67,693,468**	**$54,576,083**		**$1,272,444,504**	**$965,981,648**	**$724,617,670**	**$2,963,043,822**	**$2,908,467,739**

Table A3b. Benefits and costs over twenty years, Ghana

Year	Costs						Adoption	Discounted monetary value of DALYs saved				Discounted net benefit
	Field trials	Seed system support	Social marketing	Maintenance breeding	Total cost	Discounted total cost		Vitamin A	Zinc	Iron	All	All
0	$854,412	$0	$0	$0	$854,412	$854,412	0%	$0	$0	$0	$0	-$854,412
1	$854,412	$0	$0	$0	$854,412	$829,526	0%	$0	$0	$0	$0	-$829,526
2	$854,412	$341,765	$170,882	$85,441	$1,452,500	$1,369,121	0%	$0	$0	$0	$0	-$1,369,121
3	$0	$341,765	$174,809	$89,368	$605,942	$554,523	0%	$716,008	$1,334,638	$975,583	$3,026,229	$2,471,706
4	$0	$341,765	$177,196	$91,755	$610,716	$542,613	1%	$1,117,641	$2,083,283	$1,522,821	$4,723,746	$4,181,133
5	$0	$341,765	$180,882	$95,441	$618,088	$533,168	1%	$1,718,616	$3,203,501	$2,341,669	$7,263,787	$6,730,618
6	$0	$341,765	$186,365	$100,924	$629,054	$526,823	2%	$2,583,399	$4,815,456	$3,519,963	$10,918,818	$10,391,996
7	$0	$0	$194,079	$108,638	$302,717	$246,137	2%	$3,757,812	$7,004,561	$5,120,138	$15,882,511	$15,636,374
8	$0	$0	$204,125	$118,684	$322,809	$254,828	3%	$5,228,350	$9,745,645	$7,123,794	$22,097,789	$21,842,961
9	$0	$0	$215,968	$130,526	$346,494	$265,559	5%	$6,884,384	$12,832,491	$9,380,192	$29,097,066	$28,831,507
10	$0	$0	$228,394	$142,953	$371,348	$276,318	6%	$8,526,130	$15,892,706	$11,617,123	$36,035,958	$35,759,640
11	$0	$0	$239,939	$154,498	$394,437	$284,950	7%	$9,939,441	$18,527,118	$13,542,804	$42,009,363	$41,724,413
12	$0	$0	$249,513	$164,071	$413,584	$290,079	8%	$10,987,720	$20,481,110	$14,971,118	$46,439,948	$46,149,869
13	$0	$0	$256,731	$171,290	$428,021	$291,461	9%	$11,647,014	$21,710,034	$15,869,427	$49,226,474	$48,935,013
14	$0	$0	$261,793	$176,352	$438,145	$289,665	9%	$11,974,537	$22,320,538	$16,315,688	$50,610,763	$50,321,098
15	$0	$0	$265,165	$179,724	$444,889	$285,557	9%	$12,056,967	$22,474,186	$16,428,001	$50,959,154	$50,673,597
16	$0	$0	$267,335	$181,894	$449,228	$279,944	10%	$11,975,191	$22,321,757	$16,316,579	$50,613,527	$50,333,583
17	$0	$0	$268,700	$183,259	$451,959	$273,443	10%	$11,790,987	$21,978,400	$16,065,595	$49,834,981	$49,561,538
18	$0	$0	$269,547	$184,106	$453,653	$266,474	10%	$11,546,703	$21,523,055	$15,732,750	$48,802,508	$48,536,035
19	$0	$0	$270,068	$184,627	$454,696	$259,306	10%	$11,269,590	$21,006,516	$15,355,175	$47,631,280	$47,371,974
Total	**$2,563,235**	**$1,708,824**	**$4,081,493**	**$2,543,552**	**$10,897,104**	**$8,773,907**		**$133,720,488**	**$249,254,995**	**$182,198,419**	**$565,173,903**	**$556,399,996**

Table A4. Sensitivity Analysis Inputs, Nigeria

Parameter	Demographic	Geography	Point Estimate	Lower	Upper	Distribution	Justification
Measles	Children 1- 4 yrs	National	5.00%	2.00%	12.00%	Triangular	IHME provided upper and lower bounds
Ratio of measles cases that result in complications	Children 1- 4 yrs	National	50.00%	30.00%	50.00%	Uniform	Two estimates found.
Xerophthalmia	Children 1- 4 yrs	National	2.20%	2.00%	2.40%	Uniform	West (2002) estimated 2.4% prevalence in Nigeria and reduced by 10% to reflect lowest possible value in country (point estimate). Lower bound further reduced by 10% to reflect changes since estimates were published in 2002.
Corneal scarring	Children 1- 4 yrs	National	0.26%	0.00%	0.26%	Uniform	No available estimates for Nigeria - used a proportion of corneal scarring to blindness estimates from the literature for point estimate and upper bound value for sensitivity analysis.
Blindness	Children 1- 4 yrs	National	0.52%	0.39%	0.68%	Triangular	IHME provided upper and lower bounds
Night Blindness	Pregnant women	National	7.70%	6.60%	9.00%	Triangular	WHO provided upper and lower bounds
Child Mortality	Children 1- 4 yrs	National	6.94%	6.36%	7.52%	Triangular	DHS provided confidence intervals as R+2SE
		North Central	3.93%	3.28%	4.58%	Triangular	
		North East	6.51%	5.61%	7.42%	Triangular	
		North West	11.66%	10.71%	12.61%	Triangular	
		South East	2.86%	2.21%	3.50%	Triangular	
		South South	2.52%	1.78%	3.27%	Triangular	
		South West	2.02%	1.55%	2.48%	Triangular	
Diarrhea	Children 1- 4 yrs	National	12.27%	6.60%	20.20%	Triangular	Point estimate calculated as an average between four age groups. Lower and upper bounds are highest and lowest of four groups.
Pneumonia	Children 1- 4 yrs	National	2.60%	0.80%	2.60%	Uniform	ARI prevalence used as proxy for pneumonia prevalence. Point estimates serve as upper bound. Lowest estimates across zones serves as lower bound.
		North Central	1.30%	0.80%	1.30%	Uniform	
		North East	8.20%	0.80%	8.20%	Uniform	
		North West	1.30%	0.80%	1.30%	Uniform	
		South East	1.60%	0.80%	1.60%	Uniform	
		South South	2.40%	0.80%	2.40%	Uniform	
		South West	0.80%	0.00%	0.80%	Uniform	
Moderate impacted physical activity	Children 1- 4 yrs	National	65.05%	63.55%	66.45%	Triangular	DHS provided confidence intervals as R+2SE. Subtracted highest point estimate (from zones) of severe anemia for upper and lower bound.
		North Central	63.00%	58.20%	64.30%	Triangular	DHS provided confidence intervals as R+2SE. Subtracted point estimate of severe anemia for upper and lower bound.
		North East	64.30%	61.40%	67.10%	Triangular	
		North West	63.20%	59.90%	66.40%	Triangular	
		South East	65.10%	61.40%	68.80%	Triangular	
		South South	68.20%	65.00%	71.30%	Triangular	
		South West	55.90%	52.00%	59.80%	Triangular	
Severe impacted physical activity	Children 1- 4 yrs	National	2.85%	2.57%	3.14%	Uniform	No additional data. Plus or minus 10%
		North Central	2.30%	2.07%	2.53%	Uniform	
		North East	3.80%	3.42%	4.18%	Uniform	
		North West	4.40%	3.96%	4.84%	Uniform	
		South East	2.50%	2.25%	2.75%	Uniform	
		South South	2.70%	2.43%	2.97%	Uniform	
		South West	1.40%	1.26%	1.54%	Uniform	
Moderate impacted physical activity	Children 5-14 yrs	National	76.70%	65.05%	76.70%	Uniform	

Severe impacted physical activity	Children 5-14 yrs	National	8.80%	2.85%	8.80%	Uniform	Point estimate came from a study in rural Nigeria. Likely an overestimate, particularly for urban regions. No additonal data. Point estimate is upper bound. National prevalence for Children 1-4 selected as lower bound.
Men affected by anemia as a proportion of women prevalences	Men 15+	National	33.33%	25.00%	50.00%	Uniform	No available estimates for Nigeria. Current estimates in Malawi show that men are affected by anemia at 25 to 50% of the rates of women for mild, moderate, and severe anemia. Some estimates of anemia in men in Malawi exceed estimates from women, particularly in higher age groups.
Moderate impacted physical activity	Women 15+	National	55.03%	53.83%	56.23%	Triangular	DHS provided confidence intervals as R+2SE. Subtracted point estimate of severe anemia for upper and lower bound.
		North Central	52.40%	49.70%	55.10%	Triangular	
		North East	54.40%	51.50%	57.20%	Triangular	
		North West	54.70%	52.20%	57.30%	Triangular	
		South East	62.20%	59.40%	65.00%	Triangular	
		South South	57.60%	54.30%	60.90%	Triangular	
		South West	50.60%	47.80%	53.40%	Triangular	
Severe impacted physical activity	Women 15+	National	1.57%	1.41%	1.73%	Uniform	No additional data. Plus or minus 10%
		North Central	1.20%	1.08%	1.32%	Uniform	
		North East	1.60%	1.44%	1.76%	Uniform	
		North West	2.30%	2.07%	2.53%	Uniform	
		South East	1.80%	1.62%	1.98%	Uniform	
		South South	2.00%	1.80%	2.20%	Uniform	
		South West	0.50%	0.45%	0.55%	Uniform	
Moderate impacted mental activity	Children 1- 4 yrs	National and Regional					See impacts from physical activity
Severe impacted mental activity	Children 1- 4 yrs	National and Regional					
Stillbirths		National	30.00%	27.00%	33.00%	Uniform	No additional data. Plus or minus 10%
Under-5 mortality rate		National	13.20%	12.39%	14.02%	Triangular	DHS provided confidence intervals as R+2SE
		North Central	9.51%	8.62%	10.41%	Triangular	
		North East	13.37%	12.10%	14.65%	Triangular	
		North West	18.75%	17.54%	19.96%	Triangular	
		South East	7.55%	6.32%	8.78%	Triangular	
		South South	7.26%	6.18%	8.34%	Triangular	
		South West	6.23%	5.51%	6.94%	Triangular	
Households that rely exclusively on breastfeeding		National	29.00%	26.10%	31.90%	Uniform	No additional data. Plus or minus 10%
Pregnancies resulting in live birth		National	76.00%	68.40%	83.60%	Uniform	DHS value for Ghana used as proxy for Nigeria. No additonal data found. Plus or minus 10%
Average maternal mortality ratio		National	0.80%	0.51%	0.80%	Uniform	Two estimates found.
Rice consumption patterns	Pregnant women	National	88.84	87.54	90.13	Triangular	Calculated SE on Stata using LSMS-ISA data. Lower and upper bounds reflect mean plus or minus 2 SE.
		North Central	71.52	69.18	73.86	Triangular	
		North East	52.76	51.21	54.30	Triangular	
		North West	50.42	48.94	51.89	Triangular	
		South East	164.91	160.95	168.87	Triangular	
		South South	129.14	125.66	132.62	Triangular	
		South West	74.66	71.75	77.56	Triangular	
	Children 1- 4 yrs	National	34.54	33.87	35.20	Triangular	
		North Central	30.26	28.94	31.58	Triangular	
		North East	23.32	22.52	24.12	Triangular	
		North West	21.99	21.27	22.72	Triangular	
		South East	67.61	65.14	70.07	Triangular	

		South South	55.44	53.36	57.52	Triangular	
		South West	29.38	27.84	30.93	Triangular	
	Children 5-14 yrs	National	36.91	36.35	37.47	Triangular	
		North Central	30.69	29.64	31.73	Triangular	
		North East	23.00	22.33	23.67	Triangular	
		North West	21.55	20.93	22.17	Triangular	
		South East	69.75	67.99	71.50	Triangular	
		South South	57.26	55.66	58.87	Triangular	
		South West	28.74	27.64	29.84	Triangular	
	Women 15+	National	97.35	96.00	98.71	Triangular	
		North Central	75.81	73.34	78.28	Triangular	
		North East	53.76	52.25	55.27	Triangular	
		North West	51.65	50.20	53.10	Triangular	
		South East	179.76	175.82	183.69	Triangular	
		South South	134.80	131.40	138.20	Triangular	
		South West	84.10	81.02	87.17	Triangular	
	Men 15+	National	94.05	92.70	95.40	Triangular	
		North Central	74.40	71.97	76.84	Triangular	
		North East	54.94	53.36	56.52	Triangular	
		North West	52.19	50.70	53.68	Triangular	
		South East	169.77	165.92	173.62	Triangular	
		South South	134.19	130.55	137.83	Triangular	
		South West	84.94	81.40	88.49	Triangular	
Nutrient content of rice	Children	National	0.750	0.68	0.83	Uniform	No additional data. Plus or minus 10%
	Adult	National	0.620	0.56	0.68	Uniform	
	All	National	0.100	0.09	0.11	Uniform	
	All	National	0.100	0.09	0.11	Uniform	
Added micronutrient content (ug per g rice)	All	National	1.000	0	6.52	Uniform	Field trial estimates. Lower bound of 0 as conservative assumption. Wide range to account for variety of soil conditions, storage, and preparation.
	All	National	0.009	0	0.019	Uniform	
	All	National	0.005	0	0.011	Uniform	
Added micronutrient content (ug per g rice)	All	National	6.520	1	6.52	Uniform	
	All	National	0.019	0.009	0.019	Uniform	
	All	National	0.011	0.005	0.011	Uniform	
Discount rate		National	3%	0%	6%	Uniform	No additional data. Plus or minus 10%
Field Trials		National	$5,348,667	$4,813,801	$5,883,534	Uniform	
Seed System Support		National	$2,139,467	$1,925,520	$2,353,414	Uniform	
Social marketing costs (base)		National	$ 1,069,733	$962,760	$1,176,707	Uniform	
Maintenance breeding (base)		National	$ 534,867	$481,380	$588,353	Uniform	
Min coverage rate		National	0.01	0	0.02	Uniform	Significant uncertainty around coverage and rate of adoption.
Max coverage rate		National	0.10	0	0.2	Uniform	
Min coverage rate		National	0.02	0.01	0.02	Uniform	
Max coverage rate		National	0.20	0.1	0.2	Uniform	
Time when adoption accelerate (year)		National	2028	2024	2038	Uniform	
Gamma		National	0.50	0	1	Uniform	