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# Economic Feasibility of Iodine Agronomic Biofortification: A Projective Analysis with Ugandan Vegetable Farmers

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**Citation:** Olum, S.; Gellynck, X.; Wesana, J.; Odongo, W.; Aparo, N.O.; Aloka, B.; Ongeng, D.; De Steur, H. Economic Feasibility of Iodine Agronomic Biofortification: A Projective Analysis with Ugandan Vegetable Farmers. *Sustainability* **2021**, *13*, 10608. https://doi.org/10.3390/su131910608

Academic Editor: Carlos Rodríguez Monroy

Received: 27 August 2021
Accepted: 21 September 2021
Published: 24 September 2021



**Abstract:** Cost–benefit analysis of (iodine) biofortification at farm level is limited in the literature. This study aimed to analyze the economic feasibility of applying iodine-rich fertilizers (agronomic biofortification) to cabbage and cowpea in Northern Uganda. Data on costs and revenues were obtained from a survey of 100 farmers, and benefits that would accrue from using iodine fertilizers were elicited using consumers' willingness to pay (WTP) for the iodine-biofortified vegetables. The cost–benefit analysis demonstrated iodine agronomic biofortification as a highly profitable effort, generating average benefit–cost ratios (BCRs) of 3.13 and 5.69 for cabbage and cowpea production, respectively, higher than the conventional production practice. However, the projective analysis showed substantive variations of economic gains from iodine biofortification among farmers, possibly due to differences in farming practices and managerial capabilities. For instance, only 74% of cabbage farmers would produce at a BCR above 1 if they were to apply iodine fertilizer. Furthermore, a sensitivity analysis to estimate the effect of subsidizing the cost of iodine fertilizer showed that a higher proportion of farmers would benefit from iodine biofortification. Therefore, as biofortification is considered a health policy intervention targeting the poor and vulnerable, farmers could be supported through fertilizer subsidies to lower the production cost of iodine-biofortified foods and to avoid passing on the price burden to vulnerable consumers.

**Keywords:** agronomic biofortification; benefit–cost ratio; consumers; farmers; iodine; willingness-to-pay

## 1. Introduction

Iodine deficiency disorders (IDDs) are a public health concern and affect approximately 2 billion people globally [1]. Iodine is an important trace element required for the proper functioning of the thyroid gland. Its deficiency, IDDs, which causes devastating health outcomes, has been primarily managed through industrial iodized table salt [2], though many communities continue to be affected by IDDs. Therefore, complementary and sustainable approaches to prevent IDDs have been recommended.

Biofortification, the process of enriching the micronutrient content of food crops during production [3], is considered a key and effective strategy to increase dietary intake of iodine [1,4]. Iodine biofortification can either be achieved through an agronomic pathway (direct agro-chemical application of iodine to crop leaves or to the soil) or a (genetic) breeding approach [1]. Although the latter seems promising, is less costly, and is more sustainable in the long run, as planting seed material remains viable for many seasons [5,6], the initial investments are high and selecting target genes as well as testing for genotype and environmental interactions takes a long time [1,7]. Hence, agronomic biofortification presents a practical and feasible alternative capable of enhancing the iodine content of staple foods in the short run. Previous studies have demonstrated the efficacy of many food crops to absorb and accumulate iodine, applied as fertilizer [4,8–11], despite also being considered relatively expensive to routinely buy and apply in rural contexts [7,12]. For example, agronomic biofortification with iron (Fe) and zinc (Zn) was found to cost between USD 376–942 and USD 311–1146 per disability-adjusted life year (DALY) saved, respectively, in China [7], whereas Zn agronomic biofortification cost an estimated USD 461–619 per DALY saved in Vietnam [13] and USD 226–574 in China [14]. Nonetheless, agronomic biofortification has an impact on health outcomes and is the most practical approach to increase the iodine content of food crops. In addition to production costs incurred, it is important to also quantify the benefits, more so in economic terms, of the biofortification strategy to establish potential trade-offs that can justify adoption among farmers. Economic incentives potentially influence the adoption of new technologies [15] and the level of economic gain from iodine biofortification is likely to vary among producers. Thus, an assessment of the costs and benefits of agronomic biofortification should account for the production practices prevalent in a given context.

Cost–benefit analysis (CBA) is used to evaluate the economic feasibility of projects so as to guide investment decisions [16,17]. When used in the agri-food sector [18], costs generally refer to the total costs incurred during the production period (e.g., field preparation, transport, agro-chemical, harvest, etc.), whereas benefits reflect the revenue received by selling the produce [16,19,20]. CBA has also been applied to analyze the economic feasibility of GM crop cultivation [15] and to support the release of GM forest crops (Kazana, et al.) [21]. The previous focus on cost-effectiveness, largely to assess the potential health impact of conventionally bred [22] and genetically engineered [23] biofortified crops at the societal level, has masked the application of CBA at the farm level. Therefore, this study aimed to fill this research gap by investigating the economic feasibility of iodine agronomic biofortification of vegetables at the farm level in Northern Uganda. In this context, additional costs incurred in novel food production are often covered by agents in production or passed to the consumers [24]. Thus, the real costs incurred in introducing iodine fertilizer in crop production will most likely be covered by the producers and/or consumers. However, as iodine is a non-essential element for plant growth [25], its application may have no significant effect on yield or other agronomic outcomes, e.g., stress tolerance, which could be a reason for adoption at the farm level [26]. In other words, farmers may not have an economic incentive to introduce iodine fertilizer into their production, unless they positively perceive possibilities of higher revenues. Therefore, the feasibility of agronomic iodine biofortification would largely hinge on higher premiums paid by consumers for iodine-biofortified foods, as previously indicated [18,24]. Therefore, we examined consumers' WTP as an indicator of the benefits of agronomically producing iodine-biofortified cabbage and cowpea.

## 2. Materials and Methods

### *2.1. Study Context and Participants*

This study focused on evaluating the costs and benefits of iodine agronomic biofortification of cabbage and cowpea in a farmer field setting of Northern Uganda. As a landlocked country with poor consumption of seafood (the only naturally abundant source of iodine), Uganda is at great risk of inadequate intake of iodine and its associated health risks, iodine deficiency disorders (IDDs). The prevalence of IDDs in the country has previously been reported to be high [27], with goiter cases (the most common manifestation of IDDs) reported to be frequently occurring in the society [28]. Our CBA focused on two crops, i.e., cabbage and cowpea. Recent agronomic experiments in Northern Uganda demonstrated that these two widely consumed vegetables are able to accumulate iodine when applied as foliar fertilizer during production [11].

The socio-economic and farm characteristics of the 100 surveyed farmers are presented in Table 1. The sample consisted of smallholder farmers operating an average 5.7 acres of land for production, with the majority of farm labor being family members of around 8 people on average. The majority of the farmers reported accessing agricultural credits and extension services to boost their production. The sample further consisted of farmers with generally low education levels, the majority at a primary education level, which was possibly also linked to the relatively limited knowledge of iodine deficiency. The majority of respondents were also characterized by low levels of household income of approximately USD 134 per month on average and had used fertilizers for around 2.2 years on average. The majority of participants also exhibited a high intention to apply iodine fertilizer (agronomic biofortification) once made available.

**Table 1.** Socio-demographic and farm-related characteristics of the farmers surveyed ($n$ = 100).

| Variable | | Min | Max | Mean (SD) | Percent |
|---|---|---|---|---|---|
| Age (years) | | 20 | 70 | 39.2 (12.2) | |
| Household size | | 1 | 30 | 8.04 (4.2) | |
| Farm size (acres) | | 1 | 30 | 5.7 (4.6) | |
| Monthly income (USD) | | 13.5 | 540.5 | 134 (100) | |
| Distance to nearest market (km) | | 0.5 | 30 | 3.7 (5.0) | |
| Experience of fertilizer use (years) | | 0 | 15 | 2.2 (2.8) | |
| Gender | Male | | | | 59% |
| | Female | | | | 41% |
| Access to agricultural credits | Yes | | | | 68% |
| | No | | | | 32% |
| Access to extension workers/advice | Yes | | | | 66% |
| | No | | | | 34% |
| Knowledge of iodine deficiency | Yes | | | | 43% |
| | No | | | | 57% |
| Source of labor used in vegetable production | Family labor | | | | 62% |
| | Hired labor | | | | 2% |
| | Both | | | | 36% |
| Level of education attained | No formal education | | | | 9% |
| | Primary education | | | | 52% |
| | Secondary education | | | | 32% |
| | Tertiary | | | | 7% |
| I intend to apply iodine fertilizer to my cowpea or cabbage | Strongly disagree | | | | 22% |
| | Disagree | | | | 16% |
| | Agree | | | | 37% |
| | Strongly agree | | | | 25% |

### 2.2. Costs and Benefits Estimation

#### 2.2.1. Costs and Benefits of Current Production

During the surveys, the sampled farmers were asked to record all the costs incurred in the current or most recent production of a given acreage of cabbage or cowpea, following the procedure by Vidogbéna et al. [29]. Data were collected on the input, investment, labor, and operational costs. In addition, depreciation costs were estimated on some farm tools (e.g., watering can), given they are often used for many production cycles or years. The input costs included those spent on purchasing seeds, chemical fertilizers, pesticides, and other inputs used in production. The labor costs included the expenditures on workers for carrying out different production activities, i.e., land clearing, ploughing, nursery bed preparation and maintenance (only for cabbage), transplanting, weeding, applying chemicals and water, harvesting, transporting, and marketing. Farm labor costs in Uganda are generally calculated based on unit area worked. For instance, land clearing costs on average about UGX 2500 (approximately USD 0.68) for an area of 2 m by 40 m in Northern Uganda. This approach was applied to verify the recalled labor cost revealed by the farmers. The calculation of farm labor costs per unit area worked is also common in other regions in Africa (see, for example, Vidogbéna et al. [29]. The labor cost was estimated in monetary value irrespective of whether a farmer used family or hired labor for a particular farm activity.

In estimating the benefits, the amount of marketable yield was recorded for each farmer and the actual revenues earned from selling the products was recorded for each crop. Given that cabbage and cowpea are both sold and self-consumed in Uganda, the amounts of products consumed by the farming household were estimated and multiplied by the market unit price of the products. The result was then added to the revenue received from part of the harvest sold. The last type of benefits was only applicable to cowpea, and included costs saved on seeds that were replanted from the previous harvest.

#### 2.2.2. Cost and Benefit Estimation for Iodine Agronomic Biofortification

In projecting the cost of cabbage and cowpea production with iodine agronomic biofortification, the cost of iodine fertilizer and the associated labor cost needed to cultivate an acre of each crop were added to the total cost of current production, as described in the previous section. As micronutrient fertilizers, such as iodine-rich fertilizers, are not currently in use in Uganda (except for research purposes), the prices of iodine fertilizers were collected and compared from agrochemical input shops in the study area (Northern Uganda). The recommended doses of iodine fertilizers per acre of production were obtained from a recent cabbage and cowpea agronomic iodine biofortification experiment in the study area [11].

The estimation of revenues from implementing agronomic biofortification by famers involved assessing consumers' willingness to pay (WTP) a premium for iodine-biofortified vegetables compared to conventionally produced vegetables. Therefore, an open-ended choice experiment (OECE) was carried out. A choice experiment is a type of stated preference method for estimating consumers' WTP, which has been widely applied in previous consumer food studies [30–32]. In such an experimental setting, participants are offered food products with different attributes and attribute levels and are asked to state their preference or WTP for a combination of attributes. The OECE has an additional advantage of allowing for an estimation of WTP for multiple units of goods. As such, it mimics the real purchase behavior of consumers who often buy more than one unit of food products in a shopping moment [18].

In this study, the OECE design was applied to elicit consumers' WTP for iodine-biofortified versus non-biofortified cowpea and cabbage in Northern Uganda. During the OECE, participants were offered different price combinations of both the conventional and the biofortified versions of each crop, and were asked to indicate the quantities that they would purchase at each price combination. For all the price combinations, the price of the conventional product was kept constant at its market value. Table 2 presents a bidding sheet, which contains all price combinations that were used in the experiment.

**Table 2.** An example of an OECE bidding form for cowpea.

| At These Prices, How Many Bundles of Cowpea Would You Buy? | | | |
|---|---|---|---|
| **Price Combinations** | | **Number of Bundles of Cowpea Desired (300 g Each)** | |
| Conventional cowpea | Iodine-rich cowpea | Conventional | Iodine-rich cowpea |
| 500/= | 300/= | … … … … … … … … … … | … … … … … … … … … … |
| 500/= | 500/= | … … … … … … … … … … | … … … … … … … … … … |
| 500/= | 700/= | … … … … … … … … … … | … … … … … … … … … … |
| 500/= | 1000/= | … … … … … … … … … … | … … … … … … … … … … |
| 500/= | 1200/= | … … … … … … … … … … | … … … … … … … … … … |
| 500/= | 1500/= | … … … … … … … … … … | … … … … … … … … … … |

Prices are in Ugandan shillings (UGX): USD 1 = UGX 3700 at the time of data collection.

Participants were also informed that they could indicate zero, in case they were not interested in buying a product at a certain price, but otherwise, they could indicate as many quantities as they desired at a given price. Thus, as applied in previous OECE studies [33,34], a consumer's maximum WTP for a single unit of each iodine-biofortified product was estimated as the highest price at which the participant stated a positive quantity of the product. The premiums for iodine-biofortified products were determined based on the difference between the price of conventional products and the stated premium for biofortified products.

### 2.3. Economic and Statistical Analyses

The amount of production of each crop (cabbage and cowpea) in a given acreage, as reported by each farmer, was translated to yield per acre for proper economic comparison and analysis [35]. Total cost was also calculated on a per-acre basis. Total income for the current production was obtained by multiplying the yield by the market price of a single unit of vegetable. Alternatively, the actual revenue earned from selling the total harvest for each vegetable was directly revealed by the farmer. In the scenario where iodine fertilizer would be applied (agronomic biofortification), the yield was multiplied by the average premium value (from the OECE) that consumers placed on each unit of biofortified product in order to obtain the income from production. The benefit–cost ratio (BCR) was calculated on the basis of the net income (benefits) divided by the total cost. A BCR greater than one indicates economic viability of a proposed action or treatment [35].

As BCR was expected to vary among the farmers studied, a generalized linear model (GLM) was run to predict how farm level and socio-economic factors would affect the level of BCR that could be attained by farmers in applying iodine fertilizer in cabbage and cowpea production. As the values of BCR (dependent variable) were non-negative, the GLM was run with a specification of Gamma distribution for the model [36].

### 2.4. Sensitivity Analysis

As it is the case with a number of interventions, the costs and benefits of iodine biofortification are expected to vary over time. Thus, we conducted a sensitivity analysis to determine the changes in benefits occurring as a result of the variation in costs and revenues for producing iodine-biofortified cabbage and cowpea. Given that the affordability of inputs, like fertilizer, is a big challenge for most smallholder farmers in developing countries, including Uganda [37,38], our sensitivity analysis particularly looked at different scenarios in which the cost of iodine fertilizer would be subsidized for the farmers by the government. The scenarios affected the total cost of production, which eventually altered the BCR for each farmer. We then reported the proportion of farmers who would produce profitably at each level of cost subsidization (0% to 50% subsidization).

## 3. Results

### 3.1. Benefits: Premium Prices for Iodine-Biofortified Cabbage and Cowpea

Consumers' average WTP for a single cabbage unit was UGX 2222 (about USD 0.6). Considering the market price for a conventionally produced cabbage, this average WTP value would result in a premium price of UGX 1222 (about USD 0.33) for iodine-biofortified cabbage. In the case of cowpea, consumers were willing to pay an average premium of UGX 1325 (USD 0.36) for 300 g of iodine-biofortified cowpea leaves. The average market price for the field substitute (conventionally produced cowpea) of the same size was established as UGX 500, indicating a premium price of UGX 825 (about USD 0.22) (Table 3).

**Table 3.** Consumers' willingness to pay for single units of iodine-biofortified cabbage and cowpea in Northern Uganda (*n* = 267).

| | WTP for Biofortified Food | | | Premium Price (UGX) | |
|---|---|---|---|---|---|
| **Products** | **Mean** | **SD** | **Median** | **Absolute Premium** | **% Conventional Food** |
| Cabbage | 2222 | 450.6 | 2500 | 1222 | 122.2% |
| Cowpea | 1325 | 272.2 | 1500 | 825 | 165% |

Prices are in Ugandan shillings (UGX). USD 1 USD = UGX 3700 at the time of data collection.

### 3.2. Average Benefit–Cost Ratio for Cabbage and Cowpea Production in Uganda

The cost–benefit analysis for an acre of cabbage in Northern Uganda is presented in Table 4. The average BCR for the current cabbage production was found to be 2.97. This ratio would increase to 3.13 if cabbage were bio-fortified using iodine fertilizer. Although this would increase the input and labor costs of the current production system, the premium that the consumers would be willing to pay for iodine-biofortified vegetables offsets these costs, hence leading to a higher BCR for iodine biofortification than the current production without iodine fertilizers.

The production of an acre of cowpea is more viable in Northern Uganda, as the BCR was higher than for cabbage production (Table 5). A BCR of 4.51 was realized for producing one acre of cowpea under the present production practice. It was projected that an average BCR of 5.69 would be realized when farmers start producing cowpea with iodine fertilizer (Table 5).

**Table 4.** Cost–benefit analysis of cabbage production in Northern Uganda. Comparison of current production versus iodine agronomic biofortification.

| Parameter | Conventional Production | | | Production with Iodine Fertilizer | | |
|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **% Total Cost** | **Mean** | **SD** | **% Total Cost** |
| Total cost | 296.92 | 183.54 | | 367.19 | 183.54 | |
| Input cost | 65.28 | 58.90 | 22.0 | 119.33 | 58.90 | 32.5 |
| Investment cost | 52.27 | 72.42 | 17.6 | 52.27 | 72.42 | 14.2 |
| Labor cost | 150.69 | 104.20 | 50.8 | 166.91 | 104.20 | 45.5 |
| Depreciation | 28.68 | 43.63 | 9.6 | 28.68 | 43.63 | 7.8 |
| Total benefit | 810.79 | 732.02 | | 1129.80 | 1030.53 | |
| **BCR** | **2.97** | **3.01** | | **3.13** | **2.94** | |

Mean and SD (standard deviation) are in USD.

**Table 5.** Cost–benefit analysis of cowpea production in Northern Uganda. Comparison of current production versus iodine agronomic biofortification.

| Parameters | Current Production | | | Production with Iodine Fertilizer | | |
|---|---|---|---|---|---|---|
| | **Mean** | **SD** | **% Total Cost** | **Mean** | **SD** | **% Total Cost** |
| Total cost | 161.24 | 63.06 | | 231.51 | 63.06 | |
| Input cost | 15.98 | 11.63 | 9.9 | 70.03 | 11.63 | 30.2 |
| Investment cost | 17.50 | 12.90 | 10.9 | 17.50 | 12.90 | 7.6 |
| Labor cost | 118.19 | 56.03 | 73.3 | 134.40 | 56.03 | 58.1 |
| Depreciation | 9.58 | 7.48 | 5.9 | 9.58 | 7.48 | 4.1 |
| Total benefit | 732.17 | 615.25 | | 1345.36 | 948.74 | |
| **BCR** | **4.51** | **3.17** | | **5.69** | **3.32** | |

Mean and SD (standard deviation) are in USD.

### 3.3. Differences in Benefit–Cost Ratios among Farmers

Although cabbage and cowpea production using iodine fertilizer would be economically viable in Northern Uganda, there are wide variations among farmers in terms of BCR. Figure 1 (cabbage) and Figure 2 (cowpea) present the variations in BCR among all farmers surveyed. Taking into account the production practices at the time of data collection, 72% of cabbage farmers were producing at a BCR greater than 1 (profitable). This proportion would increase to 74% if surveyed farmers were to apply iodine fertilizer (Figure 1). For the case of cowpea production, 90% of the surveyed farmers were producing at a BCR above 1, but this share would be higher (96%) if they were to use iodine fertilizer (agronomic biofortification) (Figure 2).

A further comparison between farmers who had previously applied fertilizers and those who had not (Figure 3) showed that previous experience in fertilizer use would result in a higher BCR of iodine biofortification than having no such experience.

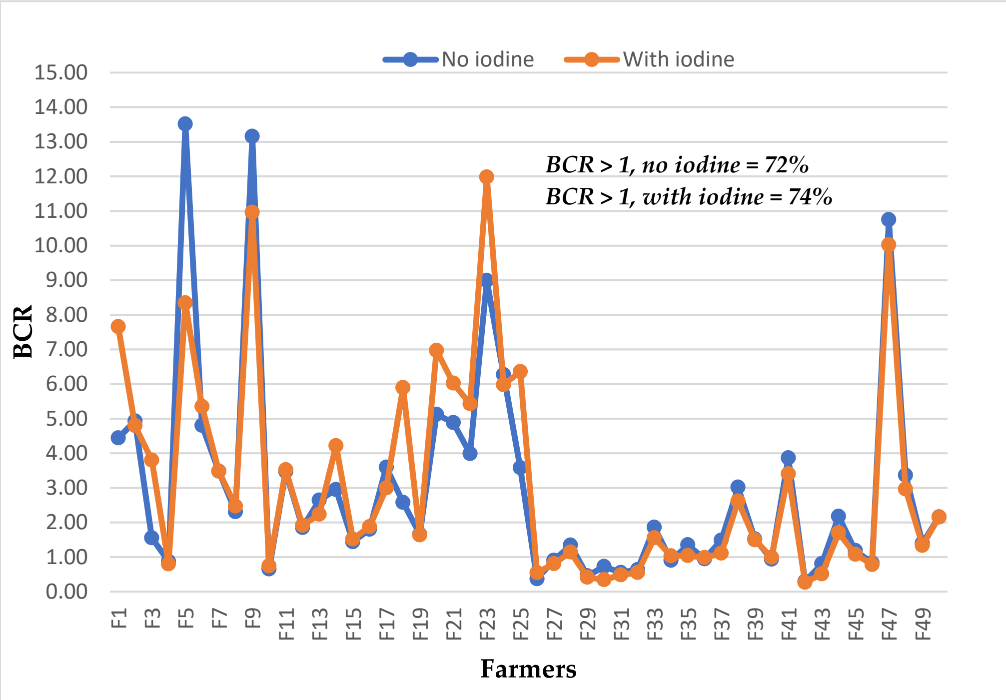


**Figure 1.** Between-farmer variation in benefit–cost ratio (BCR) for current production of cabbage versus projective cultivation with iodine fertilizer in Northern Uganda.

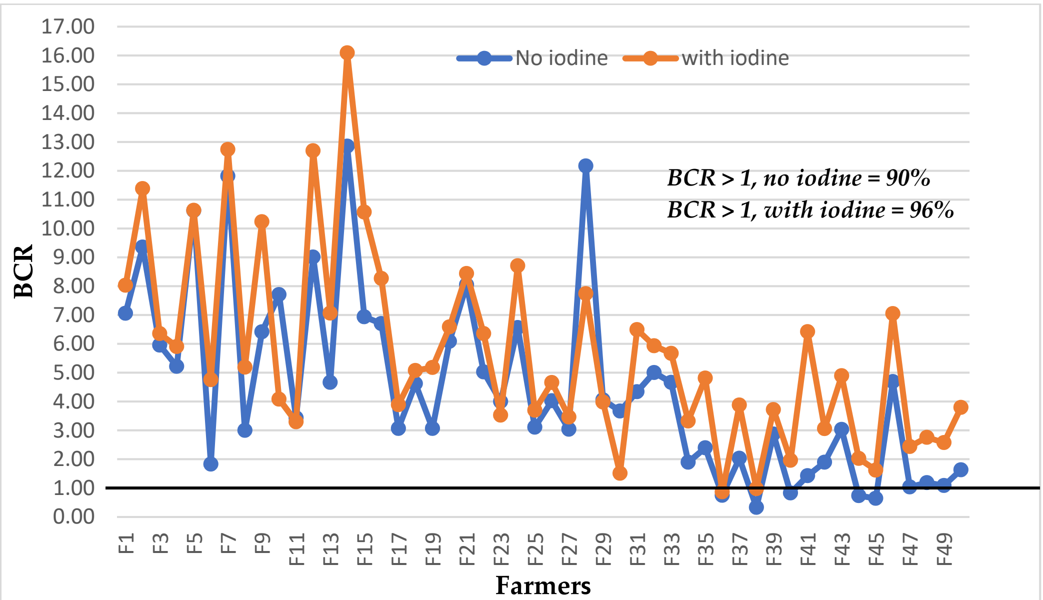


**Figure 2.** Between-farmer variation in benefit–cost ratio (BCR) for current production of cowpea versus projective cultivation with iodine fertilizer in Northern Uganda.

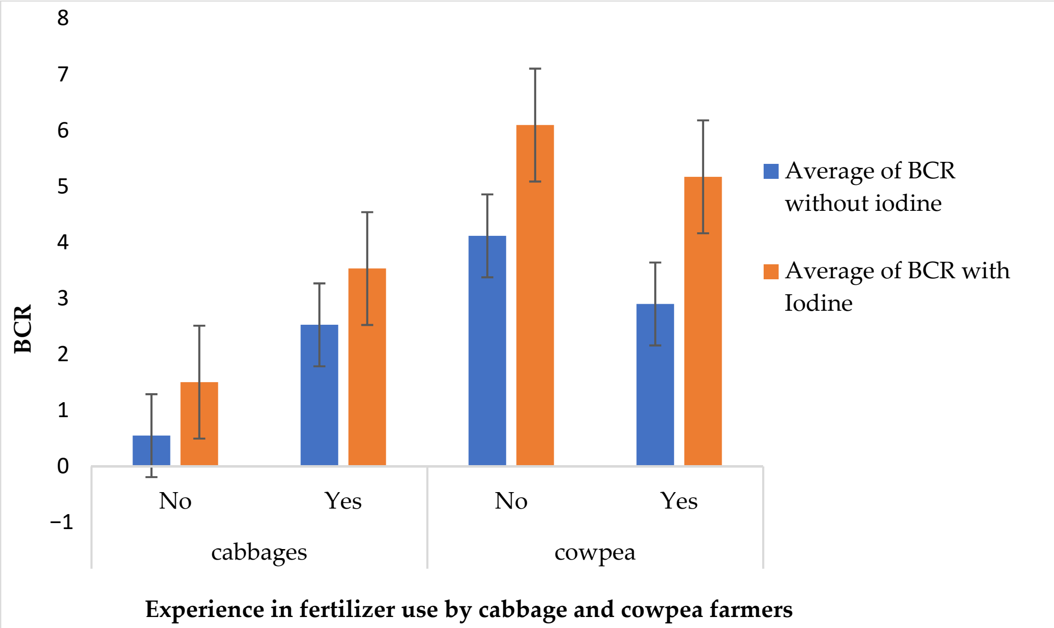


**Figure 3.** Projected effect of chemical fertilizer application experience (yes or no) on benefit–cost ratio (BCR) for cabbage and cowpea production with and without iodine fertilizer (biofortification).

### *3.4. Predictors of Benefit–Cost Ratio*

The GLM results presented in Table 6 show that the level of profitability from iodine agronomic biofortification, estimated in terms of BCR, would depend on the crop type, monthly household income, and experience with fertilizer use. The results in Figure 3 further show that when farmers have experience in chemical fertilizer application, their average BCR for iodine agronomic biofortification would be higher than when producing without iodine fertilizer.

**Table 6.** Predictors of benefit–cost ratio for iodine agronomic biofortification of cabbage and cowpea.

| Predictor | Coeff. | Std. Error | Sig. |
|---|---|---|---|
| Age | 0.003 | 0.007 | 0.688 |
| Crop type (1 = cowpea; 0 = cabbage) | 0.670 | 0.239 | 0.005 ** |
| Gender | 0.049 | 0.268 | 0.854 |
| Household size | −0.005 | 0.020 | 0.791 |
| Farm size (acres) | −0.021 | 0.017 | 0.215 |
| Experience of fertilizer use (years) | −0.051 | 0.031 | 0.099 * |
| Access to agricultural credit | 0.129 | 0.164 | 0.431 |
| Access to extension | 0.014 | 0.170 | 0.935 |
| Monthly income | 0.001 | 0.003 | 0.009 ** |
| Constant | 0.516 | 0.533 | 0.332 |
| Log likelihood | −231.392 | | |

** Significance at 5%; * significance at 10%.

### *3.5. Sensitivity Analysis Results*

Considering the variation in BCR among the sampled farmers, five scenarios were created that consisted of subsidizing the cost of iodine fertilizer for the farmers. As presented in Table 7, all the cowpea farmers surveyed would carry out iodine agronomic biofortification profitably after receiving iodine fertilizer at a 20% subsidized price. However, the cabbage farmers would need more than 50% subsidization of the cost of iodine fertilizer for all to produce at a BCR above 1 (Table 7). Given this change in profitability, subsidization of the cost of fertilizer could help to promote the uptake of agronomic iodine biofortification by the farmers in Northern Uganda.

**Table 7.** Projected effect of subsidization of iodine fertilizer cost on the benefit–cost ratio of producing one acre of iodine-biofortified cowpea and cabbage (sensitivity analysis).

| Scenario | Cowpea | | | Cabbage | | |
|---|---|---|---|---|---|---|
| | BCR (Mean) | St. Dev | %BCR > 1 | BCR | St. Dev | %BCR > 1 |
| No subsidization | 5.69 | 3.32 | 96 | 3.13 | 2.94 | 74 |
| 10% cost reduction | 6.32 | 3.69 | 98 | 3.47 | 3.26 | 78 |
| 20% cost reduction | 7.11 | 4.15 | 100 | 3.91 | 3.67 | 82 |
| 30% cost reduction | 8.12 | 4.74 | 100 | 4.47 | 4.20 | 86 |
| 40% cost reduction | 9.48 | 5.53 | 100 | 5.21 | 4.89 | 86 |
| 50% cost reduction | 11.37 | 6.63 | 100 | 6.25 | 5.87 | 92 |

St. Dev: standard deviation; %BCR > 1: proportion of farmers with a BCR greater than 1.

## 4. Discussion

This study carried out a CBA for iodine biofortification versus the current production of cabbage and cowpea at a farmer field setting in Northern Uganda. Premium prices were used to estimate the potential revenues that farmers can achieve by producing iodine-biofortified vegetables. Previously, stakeholders in the country have been shown to hold a positive perception on agronomic iodine biofortification [28] and to have a high willingness to include iodine-biofortified foods in their family and school diet [39]. The results confirmed the positive perception and preference of consumers towards the consumption of iodine-biofortified foods produced in Uganda. The higher premiums that consumers are willing to pay for iodine-biofortified products could help cover the extra costs that farmers will incur when purchasing iodine-rich fertilizers. In a previous study, which also applied consumer WTP in CBA, Kawata and Watanabe [24] found that the consumers' premium was enough to cover the extra associated cost of producing *Campylobacter*-reduced chicken, compared to normal chicken production. A similar observation was made in the study of Pappalardo et al. [18], in which consumers' additional WTP was sufficient to cover the cost of high heat treatment in pasta production. This implies that the extra cost of iodine enrichment can be adequately covered from the sale of products, and this can act as an incentive to motivate farmers to adopt iodine biofortification. It should, however, be noted that crop biofortification is a health policy intervention targeting the poor and vulnerable, who often have micronutrient deficits. Thus, farmers should be supported to further lower production costs and not pass on the price burden to consumers, as indicated in our findings.

### *4.1. Benefit–Cost Ratios*

The BCRs of 3.13 and 5.69 for the production of iodine biofortified cabbage and cowpea, respectively, indicate that this strategy would be economically viable in Northern Uganda. Comparable results were obtained in previous studies by Abdul Rahman et al. [40] and Singhal et al. [41], who carried out a benefit–cost analysis of using nitrogen fertilizers and water-soluble fertilizer in cowpea production in West Africa and India, and obtained BCRs of 2.7–4.6 and 3.4, respectively. The BCR for cabbage production in the current study is also comparable to those obtained by Vidogbéna et al. [29] in their CBA on the use of insect nets to control pests in cabbage production. However, the BCR for producing cabbage using iodine fertilizer obtained in the current study is much lower than those obtained in the study by Amoabeng et al. [35], who investigated the economic viability of using botanical insecticides to control cabbage pests in Ghana. They obtained BCRs as high as 1:29 and 1:25. The difference between their results and ours could technically be related to the fact that their study considered only the cost related to plant protection (insecticide use), whereas the benefits referred to the income from the total cabbage yield. We analyzed the total cost of producing cabbage by applying iodine fertilizer (total production cost), increasing the total cost and lowering the BCR as compared to those obtained in the aforementioned study. This is particularly important, as it illustrates the economic effect of the intervention (iodine biofortification) on the overall production, as also reported in the studies by Amulen et al. [19] and Vidogbéna et al. [29].

When comparing the current production of cabbage and cowpea in Northern Uganda to the projected production with iodine fertilizer, the latter would be more economically viable compared to the current production. This difference is a result of differences in costs and revenues that would be earned from each production practice. For instance, for an acre of cabbage production, on average, the total cost of current production is USD 297. This cost would increase to USD 367 if farmers were to biofortify their production. This difference was caused by the additional iodine fertilizer cost and the associated labor cost. However, due to consumers' higher WTP for iodine-biofortified cabbage compared to non-biofortified products, the total revenue earned from iodine biofortification (USD 1130) would be higher than that from current production (USD 811), leading to a more economically viable production, with iodine agronomic biofortification, than the current cabbage production. The same explanation applies to the differences in BCR for cowpea production with and without iodine fertilization. The implication of this finding is that the economic viability of iodine biofortification will not only depend on farmers' production capabilities (e.g., economy of scale), but also largely on how much more consumers are willing to pay for the biofortified foods compared to the field substitutes.

The BCR for iodine agronomic biofortification is positively predicted by the level of household income and crop type, with cowpea appearing to be more economically viable compared to cabbage. The difference between the two crops can be explained by the difference in production cost. Cabbage production involves sowing and maintaining the crop in the nursery bed for some weeks before transplanting to the main field, whereas cowpea seeds are sown directly in the main field, hence the lower costs (see Tables 4 and 5 for total costs). Another explanation for this difference is that iodine-biofortified cowpea would generate a higher premium (additional WTP) compared to biofortified cabbage (see results in Table 3). This would result in a higher benefit and, with a lower overall cost of cowpea production, a better BCR compared to cabbage production. However, this result may not apply to all situations. One must separate the effect of the study location. For instance, in Northern Uganda, cowpea is eaten more often (and by more households/people) than cabbage, which could explain the higher willingness to pay (premium) for cowpea compared to cabbage, something that might differ elsewhere. Nevertheless, these results suit the target of biofortification, which is to improve the micronutrient content of food crops that are already liked and eaten in big quantities by poor people, especially in developing countries [5]. The results confirm the previous assertion that the societal cost-effectiveness of biofortification depends on the micronutrient–crop combination targeted [42,43]. The positive influence of household income on BCR could reflect the ability of high-income households to purchase iodine fertilizers and meet the associated labor cost. A lack of capacity to pay for farm-level innovations, including inputs such as fertilizer, has been cited as one of the causes of low uptake of agricultural innovations in developing countries. In fact, it has been proven that as income increases, farmers are willing to pay more for farm innovations [44,45]. The positive effect of household income on BCR could therefore reflect the ability of high-income farming households to invest more in iodine biofortification than low-income households, hence the higher BCR.

### *4.2. Differences in BCR among Farmers*

The variation among sampled farmers, in terms of the BCR, indicates that some farmers would benefit from iodine agronomic biofortification, whereas others currently would not. Even among those who would benefit, the level of economic gains would vary. This is expected due to differences in managerial and agronomic capabilities among farmers, as also noted by Flannery et al. [15]. Vidogbéna et al. [29] suggested that the difference in BCR among cabbage farmers was attributable to differences in knowledge and farming practices. Our CBA was based on the prevailing farming practices at the time of the study, which are expected to vary among farmers. In our study, differences in BCR could be related to experience in fertilizer use, as farmers who have previously applied chemical fertilizer would likely benefit more from iodine fertilizer application (agronomic biofortification) than those who have no such experience, as shown in the results.

Although the sensitivity analysis results showed that a substantial proportion of farmers could produce profitably after subsidization of the costs involved in introducing iodine fertilizer, some farmers simply have a poor cost structure that would prevent them from producing profitably. For instance, the proportion of farmers with a BCR above 1 was levelled at 96% after subsidizing 20% of the cost of iodine biofortification of cowpea (see Table 7), suggesting that the remaining 4% of the farmers have a very low cost structure, perhaps because they have a low use of certain inputs like chemical fertilizers. With the introduction of iodine fertilizer and the associated costs, their costs are escalated, resulting in non-profitable production. Vidogbéna et al. [29] found out that the labor cost for pesticide use was correlated with the frequency of pesticide use, which differed among farmers and provides the explanation for the variation among farmers. According to Katungi et al. [46], only 30% of the farmers in their sample incurred the cost of plant protection, which would lead to differences in profitability among farmers. In summary, the variation in BCR among farmers can be attributed to the differences in agronomic and management practices. Thus, the promotion of iodine agronomic biofortification should be careful of the heterogeneity among farmers, including the gap in experience with fertilizer application.

## 5. Conclusions

The study carried out a CBA of iodine agronomic biofortification in a farmer field setting in Northern Uganda. The results revealed that iodine agronomic biofortification would be more economically viable than the current production practice. The viability, however, depends on crop type. Considering the two crops studied, cowpea was seen to be a more profitable crop for iodine biofortification than cabbage, mainly because of the lower production cost but also the relatively higher premium that consumers were willing to pay for iodine-biofortified cowpea compared to cabbage. This is important for guiding the choice of crops to biofortify, which should be well liked and consumed in high quantities in a particular location. It will also be crucial to promote the production of iodine-biofortified staples. However, one of the most important findings of our study is that a substantial proportion of smallholder farmers in Northern Uganda would implement iodine agronomic biofortification at BCRs below 1 (non-profitable range), according to their current practices. This is considered an important finding, as the majority of cost–benefit studies have reported only average values, which are largely affected by outliers. Knowing this proportion helps guide the selection of support for smallholder farmers to improve the nutrient density of food crops, which would eventually improve micronutrient intake and prevent deficiencies. For instance, we carried out a sensitivity analysis to predict the proportion of farmers who would produce profitably if the cost of iodine fertilizer were to be subsidized at varying levels for smallholders. Subsidies could also be established to cover the premium value of biofortified crops in order to avoid passing additional costs to consumers.

The study is considered the first to analyze, in monetary terms, the costs and benefits of iodine biofortification at the farm level, with a focus on smallholders from a developing country as the key target group of biofortification. In addition, it points to the need to carefully choose crops when planning iodine biofortification in a particular location. Finally, the study advances a step further in the literature by integrating consumers' WTP into an ex-ante cost–benefit study on farmers' potential adoption of iodine biofortification.

**Author Contributions:** Conceptualization, S.O., H.D.S. and X.G.; methodology, S.O., N.O.A. and B.A.; formal analysis, S.O., J.W. and N.O.A.; investigation, N.O.A., B.A. and W.O.; data curation, S.O., N.O.A., B.A. and W.O.; writing—original draft preparation, S.O., J.W. and W.O.; writing—review and

editing, X.G., D.O., H.D.S., B.A. and N.O.A.; supervision, X.G., D.O. and H.D.S.; All authors have read and agreed to the published version of the manuscript.

**Funding:** This study was conducted within the framework of the project "Agronomic iodine biofortification to increase iodine intake in Northern Uganda: a stakeholder-based intervention". The project is funded by the Flemish inter University Council (VLIR) TEAM Project 2016 (ZEIN2016PR429).

**Institutional Review Board Statement:** The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by Gulu University Research Ethics Committee (GUREC).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** Data could be provided when requested.

**Conflicts of Interest:** The authors declare no conflict of interest.

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