

Experimental Comparison of Bean Yields and Consumer Acceptability of Biofortified and Conventional Beans in Burundi

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Abstract

Biofortified beans enriched with iron and zinc have demonstrated their potential to address micronutrient deficiencies responsible for numerous physical and intellectual developmental problems in children, as well as maternal mortality. This study aims to provide data on the combined agronomic performance and consumer acceptability of biofortified beans compared to conventional beans. The experiment was conducted in the Giheta district of Gitega province. Using a randomised complete block design (RCBD), eight bean varieties (Rufutamadeni, Kinure ndende, Kinure ngufi, Mugwiza, Musengo, Muhoro, Magorori, and Mukungugu) were cultivated, each with three replicates. For acceptability, a sample of 30 participants randomly selected took part in a sensory evaluation to analyse consumer perceptions of the eight dishes prepared from the eight bean varieties. The Mann-Whitney test shows no statistically significant difference in yield between biofortified and conventional beans. However, a favourable yield trend was observed for biofortified beans (1157.16 kg against 934.77 kg). The Kruskal-Wallis also demonstrated that all varieties exhibited comparable yields, with a promising trend for the Mukungugu variety, which reached its potential yield. The OLS model revealed that vegetative factors (plant height, angle diameter, and number of leaves per plant) contributed more to increased bean yield than productive factors (average

number of flowers per plant, average number of pods per plant, and average pod length). The integration of innovative fertilization practices (a combination of mineral fertilizers and organic manure) and the use of biofortified bean seeds significantly contributed to increased yield. In addition to this promising trend in terms of yield, biofortified beans are also increasingly appreciated by consumers for their excellent taste and short cooking time. Their ease of preparation is also a factor in their preference. Overall, biofortified beans are a naturally best and most sustainable way to combat malnutrition and preserve the future generation.

Keywords

Biofortified Bean, Conventional Bean, Yield, Nutrition, Burundi

1. Introduction

Malnutrition is a public health problem in Burundi. Despite a decrease in the overall prevalence of malnutrition, micronutrient deficiencies persist as a significant challenge across all age groups [1]. Iron and zinc deficiencies are the most widespread in the country, causing serious problems with children's physical and intellectual development and jeopardizing the future of all generations, and causing death for women of childbearing age [2]-[5]. The adoption of micronutrient-rich crops, particularly beans, often called "the poor man's meat," is becoming essential to reversing this trend.

Beans (*Phaseolus vulgaris* L.) are a dietary cornerstone in Burundi, supplying nearly half of the population's daily protein intake and one-fifth of caloric needs [6]. Given this central role, beans have been identified as an effective vehicle for biofortification, a strategy that enhances the nutritional quality of crops through conventional breeding, agronomic practices, or genetic approaches [7]. Iron and zinc-enriched bean varieties have been introduced in the country as a sustainable means of addressing widespread micronutrient deficiencies [8]. Beyond their nutritional value, beans are deeply integrated into Burundian farming systems and cultural practices: they are cultivated by the majority of smallholder farmers, consumed almost daily across households, and contribute to both soil fertility through nitrogen fixation and household cash income from surplus sales [9]. National statistics indicate that beans occupy about 45% of the annual harvested area, ranking third in production volume after banana and sweet potato [10] [11]. With per capita consumption estimated at 45 - 50 kg per year, the highest in the region [12] [13] and productivity showing notable improvements under recent flagship interventions, beans remain central to food security, nutrition, and rural livelihoods in Burundi.

In developing countries such as Burundi, biofortification offers a sustainable, long-term solution to malnutrition because it occurs at the production stage, unlike food enrichment during processing [14]. It integrates easily into existing food systems by substituting nutrient-poor varieties with nutrient-rich ones [15]. It im-

proves health without requiring significant changes in diet or lifestyle [16] [17]. Studies showed that consuming iron-fortified food could cover up to 80% of the average daily iron requirement [17]-[19]. Consuming iron-fortified beans has been shown to prevent and correct iron deficiencies in young women, as demonstrated by [20]. Furthermore, findings revealed that young Rwandan women exhibited significant improvement in iron status and subsequently physical efficiency by consuming bio-fortified beans [20] [21]. Another research found that consuming Iron-Biofortified Pearl Millet improved cognitive functions (attention and memory) in adolescent school-aging, cognitive and physical abilities after consuming these beans [22]. All of these arguments support the inclusion of bio-fortified foods in our diets to combat malnutrition.

Despite the importance of beans, at the farmer level, bean yields remain below the expected average. This low yield is largely due to the use of unproductive planting material (unimproved conventional beans) that is susceptible to diseases and pests, the lack of integrated pest management, limited farmer knowledge, low incomes to purchase plant protection products, soil infertility, climate variability, etc. [23] [24]. A recent study in Burundi proved that small-scale producers of bio-fortified beans have a high yield compared to those who practice conventional bean agriculture (1474.513 kg vs 679.521 kg) [1]. Therefore, adopting high-yielding, nutritious varieties such as biofortified beans is essential for ensuring good production and food security in households to eradicate all forms of malnutrition, since it's proven that biofortification not only targets an increase in nutrient levels in staple crops required for improving human nutrition but also yield and preferred agronomic traits [25] [26].

Currently, the scientific literature highlights the nutritional preeminence of biofortified beans; however, important gaps remain in research to determine whether these varieties equal or surpass conventional beans in terms of agronomic performance, while also meeting the preferences of Burundian consumers. In particular, the lack of integrated studies combining agronomic, sensory, and acceptability analyses constitutes a major gap that this study aims to fill. Accordingly, this study is therefore motivated by the need to produce integrated, comprehensive evidence that combines agronomic performance data and consumer perceptions to better inform the promotion, adoption, and nutritional impact of biofortified bean varieties.

2. Materials and Methods

This experimental study was conducted in a rural setting in the Giheta area on the Bihororo and Ruhanza hills, in the commune of Giheta (Gitega province, Burundi), during the growing season B extending from February to June. The soil in the study area has a sandy-silty texture, favorable for the cultivation of beans.

2.1. Biological Material

The plant material consisted of eight bean varieties supplied by the National Cen-

tre for Agricultural Research of Burundi and distributed and recommended in the Kirimiro region. Among them, three are twining (*Kinure ndende*, *Kinure ngufi*, and *Muhoro*), and five are semi-volubles (*Mugwiza (RWR2154)*, *Musengo (MLB122-94B)*, *Rufutamadeni*, *Magorori*, and *Mukungugu*). Overall, three varieties are conventional (*Rufutamadeni*, *Kinure ndende*, and *Kinure ngufi*) and five are bio-fortified (*Mugwiza*, *Musengo*, *Muhoro*, *Magorori*, and *Mukungugu*).

2.2. Experimental Design

The trial was conducted using a randomized complete block design (RCBD), covering eight treatments, each corresponding to a bean variety (*Phaseolus vulgaris* L.). Due to the smaller quantity of seeds provided by the research center (ISABU), each treatment was repeated three times, resulting in a total of 24 elementary plots. The total area used for the experiment was 34.71 ares, corresponding to an average area of 1.44 ares per elementary plot.

The plots were set up with a spacing of 0.75 m between blocks and 0.50 m between plots to limit edge effects and interactions between treatments. The orientation and arrangement of the blocks were established to reduce soil fertility and moisture gradients, in accordance with the principles of agricultural experimentation.

Randomization of treatments within each block was performed randomly to ensure statistical independence and minimize bias. This design enables a rigorous assessment of intervarietal variability while controlling for the effects of environmental heterogeneities.

2.3. Experimental and Cultivation Procedures

This experiment was conducted under natural climate conditions and during the rainy season (season B). Sowing was carried out in rows with two seeds per pocket for both climbing and bush beans. The spacing was 40 cm between rows, 20 cm between pockets for bush beans, and 50 cm between rows and 20 cm between pockets for climbing beans [27].

Manure was applied as a base dressing at a rate of 10 tons per hectare, while organo-mineral fertilizer FOMI-IMBURA (NPKCaMg: 9-22-4-13-2) was used at a rate of 150 kg per hectare for voluble and semi-voluble beans, and 10 tons per hectare of manure and 100 kg of organo-mineral fertilizer FOMI-IMBURA for dwarf beans during sowing as indicated by ISABU [24] [27]. Weeding was carried out 3 weeks after sowing, and regular weeding was carried out thereafter to maintain the trials' permanent cleanliness, and no pest or plant disease was declared. The stakes were installed before the bean showed its ability to climb. Harvesting was carried out at the physiological maturity of the seeds, which occurred at an average of 92 days.

2.4. Data Collection

For the present study, we collected agronomic and consumer acceptability data.

For agronomic data, they were collected throughout the cropping cycle using standard measurement protocols. Both qualitative and quantitative variables were taken into account. Qualitative variables concern the description, management, and site characteristics, including fertilization type (mineral or organo-mineral), soil type (loamy or sandy), and previous land occupation (cereal or fallow). Quantitative variables included the emergence rate of the plant, plant height (cm), number of leaves per plant, number of flowers per plant, number of pods per plant, pod length (cm), and 100-seed weight (g). Measurements were taken on representative plants per plot, and mean values were computed for each variety.

2.5. Analytical Framework

To compare the yield of conventional and biofortified beans, we first need to describe statistical variables, and after, we used the Shapiro-Wilk test of normality because the sample size was small [28]. Because the simple size doesn't obey the Central limit theorem ($n < 30$) [29], nonparametric tests (Kruskal-Wallis, Mann-Whitney) are valid for comparing the yield across bean varieties or categories [30].

For assessing the influence of morphological traits and yield components on yield, we used a stepwise Ordinary Least Squares to include variables that are as orthogonal as possible to each other [31]. The global model used is the following:

$$Y_i = \beta_0 + \sum_{i=1}^n \beta_i X_i \quad (1)$$

where:

- ✓ Y_i is the yield of the bean;
- ✓ X_i the parameters taken into account that influence the yield.

Multiple tests were conducted to verify the model's robustness. The regression specification error test of [32] was performed to detect general functional form misspecification. The normality and constant variance (homoscedasticity) of the residuals were also verified with the Shapiro-Wilk test [33] and the Breusch-Pagan test [34]. The significance of the coefficient was verified with the Wald test [35].

To assess consumers' acceptability of nutrition perceptions, Fisher's exact test was used.

Following the bean harvest in the 24 randomized blocks, a sample of 30 participants was randomly selected to take part in a sensory evaluation designed to analyze consumer perceptions of eight dishes prepared from the harvests of the eight bean varieties. The evaluation focused on four predefined criteria: taste, growing cycle length, cooking time, and texture. A rating grid was used, with a score scale from 0 to 10 for each criterion and for each dish, based on consumer appreciation. Each participant evaluated all eight dishes. The individual scores were then aggregated, and the averages calculated to obtain an average score for each criterion, which served as the basis for the analysis of consumer perception. From the average scores obtained, a Likert scale was appropriately constructed for all criteria.

3. Results Presentation and Discussion

3.1. Description of the Yield of the Grown Varieties

During the experimentation, we grew eight varieties of beans distributed in bio-fortified and conventional beans. Among the eight, we had five (5) biofortified bean varieties, namely: Magorori, Mugwiza, Muhoro, Mukungugu, and Musengo. For the conventional ones, we had three varieties, namely: Kinure ndende, Kinure ngufi, and Rufutamadeni. The following table shows the descriptive statistics and mean comparison of the bean yield.

Results of **Table 1** indicate that, except Mukungugu, no other variety reached its potential yield. The observed mean yields (639 - 1585 kg/ha) remain below the potential levels (1000 - 2000 kg/ha) [27]. This can be explained by the drought, which occurred during the first period of sewing. The student's test of mean comparison between potential and observed yields across bean varieties indicated significant yield gaps for Kinure ndende, Kinure ngufi, Magorori, Musengo, and Rufutamadeni, demonstrating that these varieties performed well below their genetic potential ($p < 0.05$). In contrast, Mugwiza, Muhoro, and Mukungugu showed no significant differences, suggesting better environmental adaptation or stable performance under prevailing conditions. For Mukungugu, even if it goes above its potential yield, the difference is not significant. To compare the mean yield among varieties, a Kruskal-Wallis test was performed. The p-value of the Chi2 test shows that there's no significant difference between the bean yield of different grown varieties. Notwithstanding, Mukungugu recorded the highest rank sum while Rufutamadeni recorded the lowest rank sum.

Table 1. Description of the yield of different bean varieties.

Variables	Obs.	Mean	Potential yield [27]	Std. Dev.	Std. Err.	95% CI		Rank sum (Kruskal-Wallis)	Prob. Chi2	Wilcoxon rank-sum	Expected Prob > z
Bean yield	24	1073.76		461.51	94.20	878.88	1268.64				
Bio-fortified bean	15	1157.16		533.02	137.62	872.46	1441.85			204.50	187.50
Magorori	3	1261.04	2000.00	425.79	245.83	752.50	1769.59	50.00			
Mugwiza	3	979.35	1200.00	311.00	179.56	607.90	1350.79	34.00			
Muhoro	3	1317.01	1500.00	384.31	221.88	858.02	1776.01	52.00			
Mukungugu	3	1585.47	1000.00	818.14	472.35	608.33	2562.61	53.00	0.11		0.31
Musengo	3	642.91	1200.00	346.23	199.90	229.39	1056.43	16.00			
Conventional bean	9	934.77		283.52	94.51	739.27	1130.27			95.50	112.50
Kinure ndende	3	1140.73	1800.00	81.67	47.15	1043.19	1238.27	46.00			
Kinure ngufi	3	1024.69	1800.00	297.07	171.51	669.89	1379.49	36.00			
Rufutamadeni	3	638.89	1000.00	139.78	80.70	471.95	805.83	13.00			

For comparing the bean yield between categories, the Mann-Whitney test was used. The results show us that the p-value (0.31) is greater than 0.05. This indicates that the yields of the two categories of beans are statistically equivalent. These re-

sults indicate that biofortification doesn't imply an increase in yield. Though the difference is not marked enough to be confirmed by this test, the results indicate a trend in favour of biofortified beans.

3.2. Analysis of the Consumers' Perception

To compare the acceptability of biofortified and conventional bean varieties according to the sensory, growing time, and practical attributes such as taste, texture, cooking time, growing period, and ease of preparation, we used Fisher's exact test [36]. This analysis aimed to identify whether consumers perceived significant differences between the two categories of beans in terms of organoleptic quality and preparation characteristics.

The results of the table below (Table 2) show a strong and significant association for the taste ($p = 0.009$) and for the cooking time ($p = 0.000$). These results indicate a clear difference between these two criteria for the two categories of beans. The biofortified beans have a better taste than the conventional ones. For the cooking time, the conventional beans are distinguished by their very long cooking time, longer than the biofortified beans, which indicates that they need more energy for cooking. On the other hand, no significant association was found for the texture, growing period, and ease of preparation.

Table 2. Consumers' perception analysis.

Acceptability criterion	Rating categories	Biofortified ($n = 15$)	Conventional ($n = 9$)	Total ($n = 24$)	Fisher's exact
Taste	Good	7 (46.7%)	9 (100%)	16 (66.7%)	0.009
	Very good	8 (53.3%)	0 (0%)	8 (33.3%)	
Growing period	60 - 90 days	6 (40.0%)	3 (33.3%)	9 (37.5%)	0.159
	100 days	6 (40.0%)	1 (11.1%)	7 (29.2%)	
	More than 100 days	3 (20.0%)	5 (55.6%)	8 (33.3%)	
Cooking time	Very short	1 (6.7%)	0 (0%)	1 (4.2%)	0.000
	Short	5 (33.3%)	3 (33.3%)	8 (33.3%)	
	Long	9 (60.0%)	0 (0%)	9 (37.5%)	
	Very long	0 (0%)	6 (66.7%)	6 (25.0%)	
Texture	Smooth	14 (93.3%)	9 (100%)	23 (95.8%)	0.625
	Soft	1 (6.7%)	0 (0%)	1 (4.2%)	
Ease of preparation	Satisfied	10 (66.7%)	3 (33.3%)	13 (54.2%)	0.092
	Moderately satisfied	4 (26.7%)	6 (66.7%)	10 (41.7%)	
	Very satisfied	1 (6.7%)	0 (0%)	1 (4.2%)	

3.3. Description of the Model's Variables

Among the variables, we have qualitative and quantitative ones. They have to be described separately.

Table 3. Description of quantitative variables.

<i>Variables</i>	<i>Mean</i>	<i>Std. Dev.</i>	<i>Std. Err.</i>	<i>[95% Conf. Interval]</i>	
Emergence Rate					
<i>Biofortified</i>	68.000	4.551	1.175	65.569	70.431
<i>Conventional</i>	68.333	5.000	1.667	64.886	71.781
Seeds per pod					
<i>Biofortified</i>	5.267	0.594	0.153	4.950	5.584
<i>Conventional</i>	5.000	1.323	0.441	4.088	5.912
100 seeds weight					
<i>Biofortified</i>	41.200	7.033	1.816	37.444	44.956
<i>Conventional</i>	42.667	2.000	0.667	41.288	44.046
Plant height					
<i>Biofortified</i>	110.667	52.805	13.634	82.462	138.871
<i>Conventional</i>	119.556	61.237	20.412	77.329	161.782
Collar diameter					
<i>Biofortified</i>	2.133	0.516	0.133	1.858	2.409
<i>Conventional</i>	2.333	0.500	0.167	1.989	2.678
Number of leaves per plant					
<i>Biofortified</i>	34.000	39.417	10.177	12.946	55.054
<i>Conventional</i>	26.222	7.579	2.526	20.996	31.448
Average number of flowers per plant					
<i>Biofortified</i>	14.867	6.479	1.673	11.406	18.327
<i>Conventional</i>	18.222	4.790	1.597	14.919	21.525
Average pod length per plant					
<i>Biofortified</i>	12.933	9.982	2.577	7.602	18.265
<i>Conventional</i>	10.667	1.936	0.645	9.331	12.002
Average number of pods per plant					
<i>Biofortified</i>	8.067	3.845	0.993	6.013	10.120
<i>Conventional</i>	7.333	2.179	0.726	5.830	8.836

Based on **Table 3**, only a few variations were found across the majority of criteria when the morphological characteristics of conventional and biofortified bean cultivars were compared. The two groups' emergence rates (68.0% vs. 68.3%) were almost the same, indicating similar seed vigor and germination ability. The average pod length (12.93 cm vs. 10.67 cm) and number of seeds per pod (5.27 vs. 5.00) of biofortified beans were marginally greater, suggesting the possibility of improved grain filling and reproductive efficiency. On the other hand, conventional beans showed slightly higher plant height (119.6 cm vs. 110.7 cm) and 100-seed weight (42.67 g vs. 41.20 g), indicating stronger vegetative development. The Collar diameter was similar between the two groups (2.13 vs. 2.33 cm), and they

had slightly more leaves per plant (34 vs. 26) but fewer flowers per plant (14.9 vs. 18.2), indicating a balance between vegetative and reproductive allocation. And finally, biofortified beans had slightly more pods per plant (8.07 vs. 7.33). Biofortified beans showed agronomic equivalency to conventional beans while maintaining competitive morphological traits and potential yield advantages.

For qualitative variables, based on **Table 4**, most of the tested plots were maintained using organo-mineral fertilizer (66.7%), while only 33.3% used just mineral manure, based on the descriptive analysis of production parameters. This indicates that farmers prefer integrated soil fertility management practices. The higher use of nutritionally enhanced genotypes promoted by agroecological programs is evident, as most plots (62.5%) were planted with biofortified bean varieties. Loamy soils constituted the majority of the samples (62.5%), with sandy soils making up 37.5%. These results suggest that the soil conditions were generally suitable for bean cultivation. Most fields (79.2%) had previously been planted with cereal crops, while only 20.8% were left fallow, implying short periods for soil regeneration. The production environment seems characterized largely by intensive and integrated management systems, which may influence the variability in bean yields and soil fertility responses.

Table 4. Description of qualitative variables.

<i>Variables</i>	<i>Freq.</i>	<i>Percent</i>
Fertilizer		
<i>Mineral</i>	8	33.33
<i>Organo-mineral</i>	16	66.67
Bean category		
<i>Biofortified</i>	15	62.50
<i>Conventional</i>	9	37.50
Soil type		
<i>Loamy</i>	15	62.50
<i>Sandy</i>	9	37.50
Soil occupation history		
<i>Cereal</i>	19	79.17
<i>Fallow</i>	5	20.83

3.4. Analysis of the Determinants of Bean Yield

The variables included in the model were selected automatically using a stepwise method, which adds explanatory variables that are statistically significant at 10 percent, ensuring a more parsimonious and robust final model. The findings reveal that, instead of reproductive features (pod number, flower number), vegetative morphological traits (plant height, Collar diameter, leaf number) have a greater effect on bean output. Using biofortified cultivars and applying organo-

mineral fertilizers are examples of cultural practices that have been shown to increase yield. Overall, the model is statistically valid and well specified ($R^2 = 0.857$; satisfactory RESET test of omitted variable: $p = 0.668$, test of multicollinearity VIF = 2.24, Shapiro-Wilk test of normality of the residuals: $p = 0.844$, Breusch-Pagan tests of heteroscedasticity: $p = 0.389$, and Wald test for testing that at least one of the coefficients is different from zero: $p = 0.000$), confirming that the combination of strong vegetative vigor and sustainable cultural practices is the main driver for improving bean yield in the studied context. The following table illustrates the results of the linear regression model.

Table 5. Determinants of bean yield.

<i>Yield kg/ha</i>	Coef.	Std. Err.	t	P > t	[95% Conf. Interval]	
Soil_type						
<i>Sandy (Ref)</i>						
<i>Loamy</i>	100.600	175.863	0.570	0.576	-276.588	477.789
Fertilizer						
<i>Mineral (Ref)</i>						
<i>Organo-mineral</i>	250.061	127.476	1.960	0.070	-23.347	523.469
Bean Category						
<i>Conventional (Ref)</i>						
<i>Bio-fortified</i>	211.925	109.717	1.930	0.074	-23.396	447.245
Plant height	5.367	1.313	4.090	0.001	2.551	8.183
Collar diameter	747.017	144.477	5.170	0.000	437.144	1056.889
Number of leaves per plant	5.473	2.080	2.630	0.020	1.011	9.934
Average number of flowers per plant	-46.945	11.581	-4.050	0.001	-71.785	-22.105
Average pod length	18.502	8.861	2.090	0.056	-0.502	37.506
Average number of pods	22.780	21.230	1.070	0.301	-22.754	68.315
_cons	-1363.978	408.117	-3.340	0.005	-2239.301	-488.656

The results of **Table 5** demonstrate that plant morphological factors have a significant impact on bean output. Specifically, there are positive and substantial impacts ($p < 0.05$) on plant height, crown diameter, and leaf number, suggesting that plant vigor is essential for productivity, particularly through improved photosynthetic capacity and efficient transfer of assimilates to reproductive organs. For the plant height, a one-centimeter increase in the plant's height contributes a yield increase of 5.367 kg per ha, which is a strongly significant contribution. An increase in the Collar diameter also contributes strongly ($p = 0.000$) to the bean yield. An additional centimeter to the Collar diameter of the beans influences an increase of the yield of 747.017 kg per ha. The number of leaves per plant positively influences the bean yield. The results show that for an increase of one leaf in the average number of leaves per plant of a field, a significant increase of 5 kg

in the yield can be reached.

On the other hand, yield is negatively impacted by the average number of flowers ($p < 0.01$), indicating that excessive blooming creates internal competition that restricts pod formation and filling. The average pod length has a little favorable impact ($p = 0.056$), which is in line with the trait's direct contribution to seed production.

Although they are only slightly significant ($p < 0.10$), agronomic techniques (organo-mineral manure use) and the selection of biofortified cultivars also have a favorable impact on yield. These patterns demonstrate how agroecological advancements have enhanced soil fertility, allowing better cultivars to reveal their full genetic potential.

4. Discussion of the Results

The results of this study show that bean yield is strongly influenced by several plant morphological variables, cultivation practices, and the variety grown. The resulting regression model has a high coefficient of determination ($R^2 = 0.86$), indicating that the included explanatory variables account for a significant portion of the yield variability. The absence of heteroscedasticity ($p = 0.3893$) and omitted variables (RESET test, $p = 0.6684$) confirms the robustness of the model.

Concerning morphological characteristics, the yield is significantly influenced by plant height, collar diameter, number of leaves per plant, average number of flowers per plant, and average pod length. Plant height contributes positively and significantly to increased bean yield. This shows that vigorous vegetative growth promotes photosynthetic capacity and biomass storage, thus leading to optimal pod filling. Those results are supported by Amanuel [37], who associates greater bean height with seed yield. For collar diameter, meanwhile, it reflects physiological robustness and the capacity to transport nutrients and water, an observation corroborated by [38], who find high yield among beans with a large collar diameter, which indicates that a larger diameter indicates greater root vigor, essential for stability and the absorption of nutrients necessary for plant growth. The number of leaves per plant also has a positive effect, which is consistent with the role of leaves as the main photosynthetic organ. A balanced leaf density promotes assimilate production and pod development, as shown by Olike *et al.* [39], who show that an above-ground dry biomass is positively correlated with the development of pods per plant.

On the other hand, the average number of flowers per plant negatively influences the yield. This result, although counterintuitive, illustrates a physiological competition effect: an excess of flowers can lead to flower drop and poor fruit set, thus facilitating the formation of productive pods. Those results reinforce the idea of [40], who find that for the most productive genotypes of beans, they adopt a yield optimization strategy based on the selection of reproductive organs and preferential allocation of resources to grain filling rather than to a large number of flowers or pods. This phenomenon is often observed under conditions of water or

nutrient stress. The mean pod length has a marginally significant positive effect. It is a good indicator of ovule fertility and efficient translocation of assimilates to seeds. These results confirm that morphological traits related to vigor and assimilate distribution are key determinants of yield.

Regarding the type of bean variety, biofortified beans demonstrated a greater positive effect on yield than conventional beans, suggesting that these varieties are distinguished not only by their nutritional richness (in iron and zinc) but also by their agronomic potential. These results corroborate those of [41], who showed that biofortified varieties developed by CIAT and HarvestPlus often exhibit better physiological adaptation and comparable, or even superior, yields to conventional varieties. This can be explained by the combined selection of productivity traits and resistance to biotic and abiotic stresses during biofortification programs.

Fertilization practices show that the application of organo-mineral fertilizers significantly increases bean yield more than the use of mineral fertilizers alone. This highlights the importance of organic matter in combination with mineral fertilizers. Organic matter improves the biological structure (biodiversity), chemical structure (availability of essential nutrients), and texture (improved cation exchange capacity) of the soil [42]. These results corroborate those obtained by [43], who demonstrated a significant increase in maize yield under integrated fertilization.

Although the silty soil type had a non-significant positive effect, the literature confirms that silty soils promote good water retention and adequate aeration and a high cation exchange capacity, which are favorable to root development [44]. However, the observed lack of significance could be related to the small sample size or to uncaptured interactions between soil texture and fertilization management.

5. Conclusions

This study assessed the agronomic performance and consumer acceptability of biofortified and conventional bean varieties cultivated under real production conditions in the commune of Giheta, Burundi. Although no statistically significant differences in yield were detected between the two bean categories, biofortified varieties demonstrated slightly higher average yields and competitive morphological characteristics compared to conventional varieties. Yield performance was largely explained by vegetative vigor, particularly plant height, collar diameter, and leaf density, indicating that physiological growth traits remain key determinants of productivity. Fertilization practices also played a significant role: organo-mineral fertilization consistently improved yields compared to mineral fertilizer alone, highlighting the importance of integrated soil fertility management.

Consumer perception results clearly showed that biofortified beans were preferred in terms of taste, an essential determinant of dietary adoption and sustained consumption. While no significant differences were observed for texture or ease of preparation, biofortified beans tended to have shorter or moderate growing cy-

cles, making them potentially more suitable for regions with variable or short rainy seasons. These findings confirm that biofortified bean varieties combine nutritional benefits with acceptable agronomic and sensory characteristics, reinforcing their relevance for combating micronutrient deficiencies in Burundi.

Overall, the study shows that biofortified beans represent a promising avenue for improving household nutrition and strengthening the resilience of the food system, particularly when reinforced by sustainable agronomic practices and adequate extension services.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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