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Genotype Selection, and Seed Uniformity and Multiplication to Ensure Common Bean (*Phaseolus vulgaris* L.) var. Liborino

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Abstract: Seed uniformity and stability testing, and multiplication, are key steps in the seed supply chain of the common bean (*Phaseolus vulgaris* L.) and other crops. Optimizing agronomical practices in these phases can ultimately ensure seed quality and availability, and germplasm prospective utilization. However, farmers have rarely standardized seed testing and propagation protocols in local common bean landraces conserved *in situ*. An example of this is the Liborino variety (var.), a promising yellow Andean common bean known for its presumably high digestibility and adaptation to the local conditions of the Cauca river canyon (northwest Andes of Colombia), but likely experiencing genetic erosion after decades of suboptimal propagation. Therefore, this work intended to evaluate and select locally adapted genotypes of common bean var. Liborino for commercial use, to be later multiplied, evaluated by participatory breeding, and eventually shared with farmers. Specifically, we evaluated 44 accessions of var. Liborino common bean in six adaption and yield field trials in the Cauca river canyon at 1100 and 1400 m a.s.l, and in AGROSAVIA's "La Selva" research station at 2100 m a.s.l. In parallel, we carried out standardized seed multiplication of a Liborino genotype using best practices to guarantee uniformity and stability. From the 44 accessions, nine were well adapted to the tested local conditions. Four of these accessions exhibited a bush type growth habit, while the remaining five were climbers. The trials revealed maximum average extrapolated yields of up to 1169.4 ± 228.4 kg ha^{-1} for the bush types (G8152) and up to 1720.0 ± 588.4 kg ha^{-1} for the climbers (G51018), both at 2100 m a.s.l. Three climbing accessions matched farmers' expectations for seed coat color and shape, according to a participatory selection exercise. Uniform and stable seed of the selected genotype was delivered in 2022 to 39 farmers, ~6.5 kg of seeds per farmer. Our results will allow implementing bean genetic improvement pipelines, promoting var. Liborino commercialization, and boosting the economic and sustainable development of the rural communities in the Cauca river canyon. Seed uniformity testing and multiplication pipelines must be extended to other bean landraces conserved *in situ*.

Keywords: farmer's variety; agrobiodiversity; *in situ* conservation; landraces; seed material

1. Introduction

Legumes are an affordable source of easy-assimilated plant protein and essential nutrients for the poor, as well as a priority in alternative source of protein in vegan diets. Legumes also provide secondary ecosystem services as forages and soil fertilizers [1]. Common bean (*Phaseolus vulgaris* L.) is grown across 23 million hectares, in a broad range that extends from the central and northern highlands of Mexico, to coastal Peru and northeastern Brazil in the south, and Eastern and Southern Africa in the east, feeding over 500 million people [2]. However, there is currently a deficit in certified seed (key to convey seed uniformity for multiplication), and local production in Central and South America. These bottlenecks translate into common bean being imported to these regions, which notably are its primary agrobiodiversity diversity centers [3,4].

Common bean diversified southwards the Americas [5,6] from a wild range in Central America [5,7,8], after which independent domestications in the southern and northern ends originated the cultivated Andean and Mesoamerican genepools [7,9,10]. The southernmost races (found in Ecuador/Northern Peru, Southern Bolivia, and Argentina) are from the Andean genepool [11], while the northernmost races (in Highland Mexico, Lowland Mexico, and Guatemala) are from the Mesoamerican genepool [12].

A highly valued bean type found in both genepools, Andean and Mesoamerican, is the yellow common bean [13]. Yellow beans are dietary staples in Eastern and Southern Africa, as well as in secluded valleys in Mexico and the northern Andes. One of the most prominent quality attributes of yellow beans is their fast cooking time (<30 min), which could convey a market preference in regions of the world where cooking fuel is limited or expensive [13]. Another appeal for consumers not used to daily bean ingestion is yellow bean's digestibility. Yellow beans are low in insoluble dietary fiber, tannins, and indigestible proteins and starch, all of which are known to increase flatulence [14]. It has also been reported that a yellow seed coat color associates with lower concentrations of polyphenolic compounds [15], empowers iron bioavailability [16] and plant defense [17].

Common bean var. Liborino is a promising Andean yellow for its high digestibility and adaptation to the local conditions in Colombia, where it is found [18]. This region, a mandatory trading path of key crop species across the Americas in pre-Columbian times [19], is considered an evolutionary cradle for common bean [5,20]. Both genepools occurred in sympatry and hybridized in this region [11,21]. The Liborino variety was named at the end of the 19th century after the main town in the region, Liborina, located in the eastern slope of the Cauca river canyon at the Colombian province of Antioquia [22]. Then it was common to find Liborino beans in farms and markers in neighboring regions, together with the nowadays-more-popular Cargamanto cultivars [18].

Nonetheless, no more than 40 family farms currently conserve the landrace *in situ*. It is now largely unknown outside the Liborina region due to the sporadic trading from the Cauca river canyon following decades of civil conflict. Coffee plantations, illicit crops [23], illegal mining [24] and the ongoing construction of the largest dam in South America, Hidroituango [25], have further displaced the once popular variety. An effect of this limited modern utilization is that Liborino bean is unexplored and likely under genetic erosion. Furthermore, farmers do not follow good practices for seed multiplication, to ensure seed quality, uniformity and trait stability [26] (e.g., in germination rate, absence of seed borne diseases, and plant uniformity).

Given the previous research gaps, the overall goal of this work was to characterize and provide selected locally adapted Liborino bean seeds for commercial use to the local farmers. As a first step, we aimed to screen a diverse Liborino panel comprising 44 genebank accessions, and screen for local adaptation and yield in six field trials spanning three contrasting altitudes. Secondly, we carried out trait uniformity testing, multiplication and release of seed for the selected genotype of common bean var. Liborino. Improving genetic resources from the local agrobiodiversity, as envisioned here, has the potential to enhance the sustainable economic development of rural communities.

2. Materials and Methods

2.1. Plant Material

A total of 44 accessions of var. Liborino were included in this study (Table 1).

Table 1. Passport identifiers and seed coat color pattern of the 44 accessions of common bean (*Phaseolus vulgaris* L.) var. Liborino panel tested. Bold lines correspond to accessions selected for yield trials. Data are as per CIAT's Genetic Resources Program with details in Table S1, and within-accession color segregation in Figure S1. Rounded shape = rounded-squared, NA: not available.

Accession	Province	Municipality	Growth Habit	Seed Color Tonality (s.l.)	Seed Shape	Seed Brightness	Altitude (m a.s.l.)
G11819	Antioquia	NA	Climbing	Yellow, Red	Rounded	Intermediate	NA
G12671	Antioquia	Medellin	Climbing	Cream, Black	Rounded	Intermediate	NA
G12702	Nariño	Pasto	Climbing	Yellow, Red	Rounded	Intermediate	2700
G12706	Nariño	Pasto	Climbing	Yellow, Brown	Rounded	Intermediate	2800
G12712	Nariño	Pasto	Climbing	Yellow, Brown	Elongated	Intermediate	2600
G50516A	Antioquia	Liborina	Climbing	Red	Rounded	Intermediate	1930
G50516B	Antioquia	Liborina	Climbing	Cream, Red	Rounded	Intermediate	1930
G50516C	Antioquia	Liborina	Climbing	Red, Cream, Black	Rounded	Intermediate	1930
G50516D	Antioquia	Liborina	Climbing	Red, Yellow	Rounded	Intermediate	1930
G50516E	Antioquia	Liborina	Climbing	Yellow, Red	Rounded	Intermediate	1930
G50516F	Antioquia	Liborina	Climbing	Red	Elongated	Intermediate	1930
G50516G	Antioquia	Liborina	Climbing	Yellow, Pink	Rounded	Intermediate	1930
G50516H	Antioquia	Liborina	Climbing	Cream, Other, Black	Rounded	Bright	1930
G50516I	Antioquia	Liborina	Climbing	Cream, Brown	Rounded	Intermediate	1930
G50516J	Antioquia	Liborina	Climbing	Black	Rounded	Intermediate	1930
G50516K	Antioquia	Liborina	Climbing	Brown	Rounded	Bright	1930
G50516L	Antioquia	Liborina	Climbing	Cream, Brown, Other	Rounded	Intermediate	1930
G50516N	Antioquia	Liborina	Climbing	Cream, Brown, Black	Rounded	Intermediate	1930
G50516O	Antioquia	Liborina	Climbing	Pink, Cream, Other	Rounded	Intermediate	1930
G50516P	Antioquia	Liborina	Climbing	Yellow	Rounded	Intermediate	1930
G50516Q	Antioquia	Liborina	Climbing	Other, Black	Rounded	Bright	1930
G50516S	Antioquia	Liborina	Climbing	Pink, Brown	Rounded	Intermediate	1930
G50516T	Antioquia	Liborina	Climbing	Brown	Rounded	Bright	1930
G50516U	Antioquia	Liborina	Climbing	Brown	Elongated	Intermediate	1930
G50834	**Antioquia**	**Santa Fe de Ant.**	**Climbing**	**Yellow, Red**	**Rounded**	**Intermediate**	1600
G50840	**Antioquia**	**Santa Fe de Ant.**	**Climbing**	**Yellow, Red**	**Rounded**	**Intermediate**	2060
G50840A	Antioquia	Santa Fe de Ant.	Climbing	Cream, Red	Rounded	Intermediate	2060
G50840B	**Antioquia**	**Santa Fe de Ant.**	**Climbing**	**Yellow, Red**	**Rounded**	**Intermediate**	2060
G50997	Antioquia	Andes	Climbing	Yellow, Red	Elongated	Intermediate	1500
G50997B	Antioquia	Andes	Climbing	Purple	Rounded	Intermediate	1500
G51013	Antioquia	Liborina	Bush	Cream, Red	Rounded	Intermediate	1930
G51013A	Antioquia	Liborina	Climbing	Yellow, Red	Rounded	Bright	1930
G51018	**Antioquia**	**Liborina**	**Climbing**	**Yellow, Red**	**Rounded**	**Intermediate**	1930
G51285	Antioquia	Liborina	Climbing	Red, Cream	Rounded	Intermediate	1930
G51285C	Antioquia	Liborina	Climbing	Brown, Other, Purple	Rounded	Intermediate	1930
G51285E	Antioquia	Liborina	Climbing	Cream, Red	Elongated	Opaque	1930
G51285F	Antioquia	Liborina	Climbing	Cream, Other, Black	Rounded	Intermediate	1930
G51285G	Antioquia	Liborina	Climbing	Cream, Other, Purple	Rounded	Intermediate	1930
G51285H	Antioquia	Liborina	Climbing	Black	Rounded	Intermediate	1930
G51433	**Antioquia**	**Santa Fe de Ant.**	**Climbing**	**Yellow, Red**	**Rounded**	**Intermediate**	1600
G916	**Antioquia**	**NA**	**Bush**	**Yellow, Brown**	**Elongated**	**Intermediate**	**NA**
G4547	**Antioquia**	**Medellin**	**Bush**	**Yellow, Red**	**Elongated**	**Intermediate**	**NA**
G8152	**Antioquia**	**Medellin**	**Bush**	**Yellow, Purple**	**Elongated**	**Opaque**	**NA**
G14172	**Antioquia**	**Medellin**	**Bush**	**Yellow, Purple**	**Elongated**	**Intermediate**	**NA**

All accessions are conserved under the genetic resources treaty of the Food and Agriculture Organization of the United Nations (FAO collection), and were transferred by the Genetic Resources Unit of the International Center for Tropical Agriculture (Biodiversity—CIAT Alliance). Accessions were chosen so that their passport descriptors matched the Liborino tag, and the seed coat color pattern coincided with the expected for Liborino beans (Table S1). Natural segregation of the landraces led to additional tonalities, so only seeds with Liborino-like yellowish coat color were retained (Figure S1).

Seeds received from the genebank had to be multiplied for the following trials. Therefore, multiplication took place during the growing season of October 2019–March 2021 in AGROSAVIA's "La Selva" research station at 2100 m a.s.l. (Rionegro, province of Antioquia, Colombia, 6°07′54.9″ N, 75°24′58.4″ W). Each accession was sowed in two rows, each with eight sites and one seed per site, adding up 800 m^2 of planting area.

2.2. Adaptation and Yield Field Trials

All 44 accessions were established in trials in three altitudes representing the natural altitudinal gradient found in the municipality of Liborina at the east margin of the Cauca river canyon, Colombia. Localities were Rodas river basin at 1100 m a.s.l. (6°45′34.0″ N, 75°49′31.5″ W), San Diego village at 1400 m a.s.l. (6°43′09.3″ N, 75°46′43.6″ W), and AGROSAVIA's "La Selva" research station at 2100 m a.s.l. (6°07′54.9″ N, 75°24′58.4″ W; 17.1 °C; 1920 mm; 78% RH). La Selva research station corresponds to the lower montane wet forest life zone, with soils classified as Andisols, Typic Fulvudands.

First season planting followed a randomized complete block design with two repetitions, each across one row, eight sites per row, and two seeds sowed per site, for a total area of 500 m^2 per locality at planting distance of 1 m × 0.5 m. Sowing took place in October 2020. Fields were rainfed using farmers' traditional management for climbing beans. Plant survival and phenology were recorded biweekly until the end of the growing cycle in March 2021. Plants that produced crop were manually harvested.

A second season of trials was completed at the same three localities only for the accessions that produced crop, evidence of a good local adaptation. A total of nine accessions were planted at each locality following a randomized complete block design, this time with three repetitions, each with three rows, eight sites per row, and two seeds sowed per site. This led to a total area of ca. 500 m^2 per locality at a planting distance of 1 m × 0.5 m. The trials were established in April 2021, and fields were also rainfed using local farmers' traditional management for climbing beans. Plant phenology was recorded biweekly until the end of the growing cycle in September 2021. Days to flowering (i.e., days from emergence to 50% of plants have set flowers) were recorded per plot. Individual plants were manually harvested to record yield traits. From a set of ten plants per plot, the number of pods and number of seeds per pod were recorded. Total yield was extrapolated to kg per hectare for each accession per locality.

During both growing seasons, plants received a fertilization rate of: 20 kg of organic material/ha, 8 kg 10-30-10 fertilizer/ha, and 20 kg of minor elements/ha. Non-limiting growth conditions were maintained, and manual weed control was applied every 25 days. Additionally, a participatory evaluation with local farmers was performed. During grain filling and harvest, farmers made a visual assessment of all genotypes, focused on plant performance as well as phenology and seed traits.

The dataset of measurements from the adaptation and yield trials was analyzed in R v.4.2.0 (R Core Team) via linear models (*lm* function) and Welch's *t*-tests (*ggbetweenstats* function from the *ggstatsplot* package). These analyses initially targeted differences between growth habits as main fixed effect. Additionally, and as a second analytical step, Tukey and Welch one-way tests were carried out within each elevation using the R-package *emmeans* as a way to contrast pairwise genotypes' reactions in terms of days to flowering and extrapolated yield (kg ha^{-1}).

2.3. Seed Uniformity and Multiplication

A total of five kilograms of seed of common bean var. Liborino were established in AGROSAVIA's "La Selva" research station at 2100 m a.s.l. (geographic coordinates same as above). A total of 100 single-seed descendent self-pollinated families were established in October 2020 by harvesting 200 out of 500 plants with individual tutoring at a planting distance of 1.10 m × 0.40 m and a total area of ca. 2200 m^2. Plants were biweekly selected based on agro-morphological traits (plants with desired growth habit and flower color) and disease response (visual inspection for symptoms of seed-borne diseases and virus infection).

Based on these criteria, a total of 200 plants were individually tagged, and referred to as families. Manual harvest was completed individually for each family in March 2021. Seeds from each family were further selected so dry seed weight fell within ±1 g from the standard deviation. Seeds were finally screened for physiological parameters (seed humidity < 14% and >80% germination rate), and kept at 6 °C to prevent diseases.

Finally, multiplication of uniform seeds was carried out for 100 selected families in AGROSAVIA's "La Selva" research station from May to October 2021. A total of 44 seeds per half-sib family were sowed in 22 sites, two seeds per site, at a planting distance of 1.10 m × 0.40 m, for a total area of ca. 880 m^2. Manual harvest proceeded as described above. Seeds were also checked for physiological parameters (i.e., seed humidity < 14% and >80% germination rate), and finally stored at 6 °C.

3. Results

3.1. Adaptation Trials across Three Altitudes for 44 var. Liborino Accessions during the First Season

We evaluated days to flowering in trials at three altitudes for 44 accessions of common bean (*P. vulgaris* L.) var. Liborino during the first season of trials in October 2020–March 2021 (Figure 1). Four accessions were precocious (grey dots in Figure 1) and reached flowering time before 40 days in the trial at 1100, and 60 days in the trials at 1400 and 2100 m a.s.l. The remaining accessions reached flowering time after these thresholds (pink dots in Figure 1).

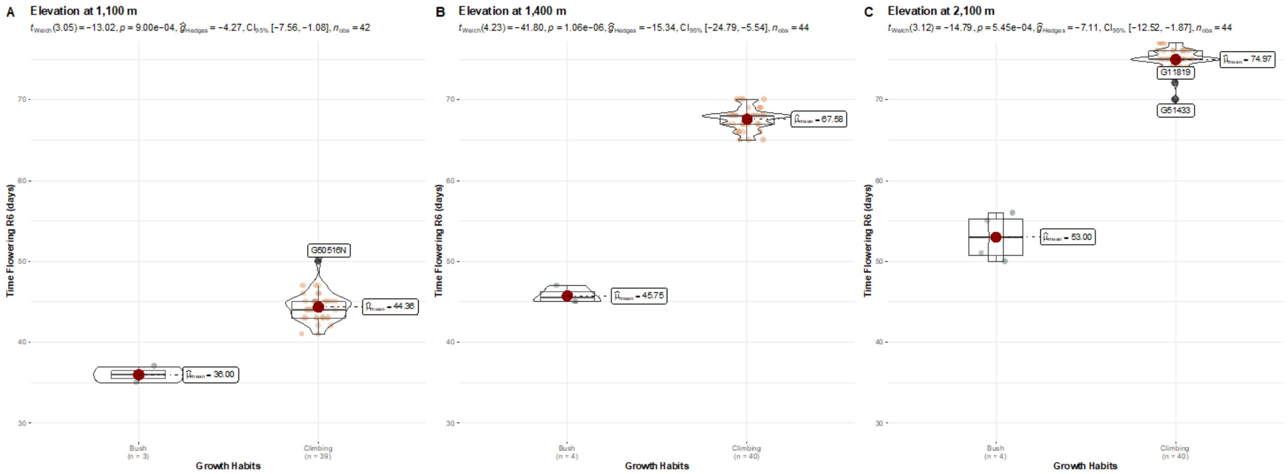

Figure 1. Average days to flowering in adaptation trials across three altitudes for 44 accessions of common bean (*P. vulgaris* L.) var. Liborino during the first season of trials (October 2020–March 2021). Altitudes are depicted as: (**A**) 1100, (**B**) 1400, and (**C**) 2100 m a.s.l. Colors of the dots indicate contrasting growth habits (grey for bush type, orange for climbers). Squared and rounded shapes mark boxplots and violin distributions, respectively. Each subfigure's title shows Welch's *t*-test, a parametric approach to compare groups when there is an imbalance in the number of individuals and homogeneity of variance cannot be assumed.

Overall, nine accessions reached harvest time. They were interpreted as locally adapted and progressed to the second season trials. Among these nine, five were climbing beans (G50834, G50840, G50840B, G51018, and G51433) and four were bush types (G916, G4547, G8152, and G14172). Four of the climbing accessions (G50834, G50840, G50840B, and G51433) were collected in the Municipality of Santa Fe de Antioquia, 22 km south of Liborina at the west margin of the Cauca river canyon, from 1600 to 2060 m a.s.l. Interestingly, climbing accession G12702 was collected from the southernmost Nariño high plateau at 2700 m a.s.l (Table 1).

3.2. Yield Trials across Three Altitudes for Nine var. Liborino Accessions during the Second Season

We evaluated total yield, yield components and days to flowering in trials at the same three locations and altitudes for nine accessions of common bean (*P. vulgaris* L.) var. Liborino that were considered locally adapted in the first season (red dots in Figure 1). Trials progressed during the second work season (April–September 2022). The nine accessions previously considered as locally adapted (based on flowering time in trials at Liborina) had enough seed material to be tested at the yield trials on the second season. In this trial, climbing beans exhibited days to flowering ranging from 56 ± 3.1 for G50840B at 1100 m a.s.l.

to 76 ± 8.9 for G51433 at 2100 m a.s.l. Meanwhile, bush beans showed days to flowering ranging from 34 ± 8.0 for G8152 at 1100 m a.s.l. to 56 ± 8.0 for G8152 at 2100 m a.s.l. Climbing beans flowered later than bush types; 65.4 ± 8.9 days vs. 41.1 ± 8.0 days for climbers and bush types, respectively (p-value = 4.1 × e^{-21}, Table 2).

Table 2. Days to flowering across altitudes (m a.s.l.) for common bean (*P. vulgaris* L.) var. Liborino accessions selected from adaptation trials. Accessions are sorted by average flowering time (FT). Tukey and Welch one-way tests were carried out within elevation using the R-package *emmeans*, as marked in the superscripts.

Accession	Growth Habit	FT at 1100 m	FT at 1400 m	FT at 2100 m
G50834	Climbing	55.3 ± 0.6^{a}	67.3 ± 2.1^{a}	74.3 ± 1.2^{a}
G50840	Climbing	50.3 ± 6.0^{a}	67.7 ± 1.6^{a}	72.0 ± 1.7^{a}
G50840B	Climbing	55.3 ± 1.2^{a}	68.7 ± 0.6^{a}	74.3 ± 2.1^{a}
G51018	Climbing	54.3 ± 1.6^{a}	68.3 ± 1.6^{a}	5.0 ± 1.0^{a}
G51433	Climbing	54.0 ± 1.7^{a}	68.7 ± 1.6^{a}	75.3 ± 0.6^{a}
G916	Bush	34.7 ± 0.6^{b}	36.0 ± 1.0^{b}	51.3 ± 2.3^{b}
G4547	Bush	35.7 ± 1.2^{b}	35.7 ± 0.6^{b}	50.7 ± 1.2^{b}
G8152	Bush	35.0 ± 1.0^{b}	36.7 ± 0.6^{b}	53.3 ± 3.1^{b}
G14172	Bush	35.7 ± 0.6^{b}	35.3 ± 0.6^{b}	52.7 ± 3.2^{b}

Accessions took more days to flower at 2100 m a.s.l. (64.3 ± 11.4), followed by Liborina localities at 1400 m a.s.l. (53.8 ± 16.4) and 1100 m a.s.l. (45.6 ± 9.7, p-value = 2.6 × e^{-07}, Figure 2). Yield components were also variable for growth habits across altitudes at the same yield trials (Table 3, Figure 3). Specifically, total number of pods was higher in climbing bean accessions than in bush types (15.7 ± 6.4 vs. 10.8 ± 4.2 for climbers and bush types, respectively, p-value = 1.8 × e^{-04}). Overall, plants set more pods in AGROSAVIA's La Selva research station at 2100 m a.s.l. (19.3 ± 5.3), followed by the trials in the two localities in Liborina at 1400 m a.s.l. (11.4 ± 1.7) and 1100 m a.s.l. (8.7 ± 3.6, p-value = 5.4 × e^{-10}).

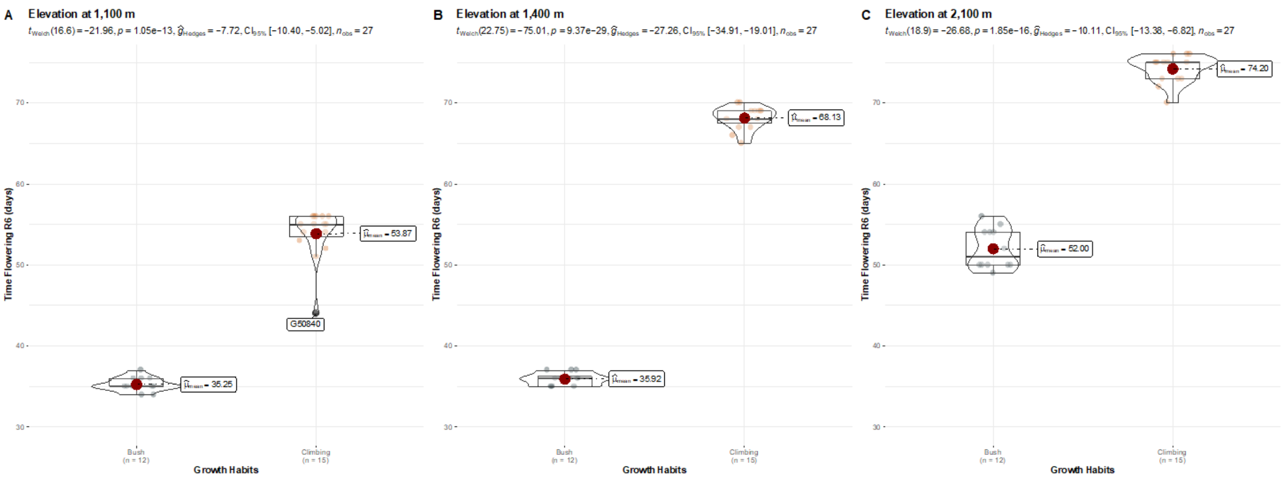

Figure 2. Days to flowering at the yield trials between growth habits across altitudes for nine locally adapted accessions of common bean (*P. vulgaris* L.) var. Liborino during the second year of trials (April–September 2022). Altitudes are depicted as follows: (**A**) 1100, (**B**) 1400, and (**C**) 2100 m a.s.l. Colors of the dots indicate contrasting growth habits (grey for bush type and orange for climbers). Squared and rounded shapes mark boxplots and violin distributions, respectively. Selected accessions from the adaptation trials were considered in triplicate at the yield trials. Subfigure's title depicts Welch's t-test given imbalance in the number of individuals and non-homogeneous variance.

Table 3. Extrapolated yield (kg ha^{-1}) across altitudes (m a.s.l.) for each accession of common bean (*P. vulgaris* L.) var. Liborino selected from adaptation trials. Accessions sorted by average yield. Tukey and Welch one-way tests were carried out within each elevation using the R-package *emmeans*, as marked in the superscripts. Differences between growth habits are reported in Figure 3. NA: not available.

Accession	Growth Habit	Yield at 1100 m	Yield at 1400 m	Yield at 2100 m
G51433	Climbing	521.0 ± 13.3 ^{a}	846.1 ± 275.7 ^{a}	1710.0 ± 471.2 ^{a}
G50840	Climbing	439.9 ± 24.2 ^{a}	670.7 ± 258.6 ^{a}	1429.8 ± 256.5 ^{a}
G50834	Climbing	428.8 ± 4.2 ^{a}	837.9 ± 473.4 ^{a}	1596.2 ± 1032.9 ^{a}
G51018	Climbing	NA	NA	1720.0 ± 588.4 ^{a}
G50840B	Climbing	418.3 ± 3.0 ^{a}	566.8 ± 223.9 ^{a}	1264.1 ± 118.5 ^{a}
G4547	Bush	629.3 ± 262.6 ^{a}	874.3 ± 307.0 ^{a}	1093.4 ± 192.2 ^{a}
G916	Bush	555.2 ± 174.2 ^{a}	726.6 ± 257.6 ^{a}	1105.3 ± 333.2 ^{a}
G8152	Bush	411.7 ± 57.7 ^{a}	852.3 ± 103.5 ^{a}	1169.4 ± 228.4 ^{a}
G14172	Bush	362.1 ± 74.9 ^{a}	552.3 ± 337.1 ^{a}	1126.2 ± 192.2 ^{a}

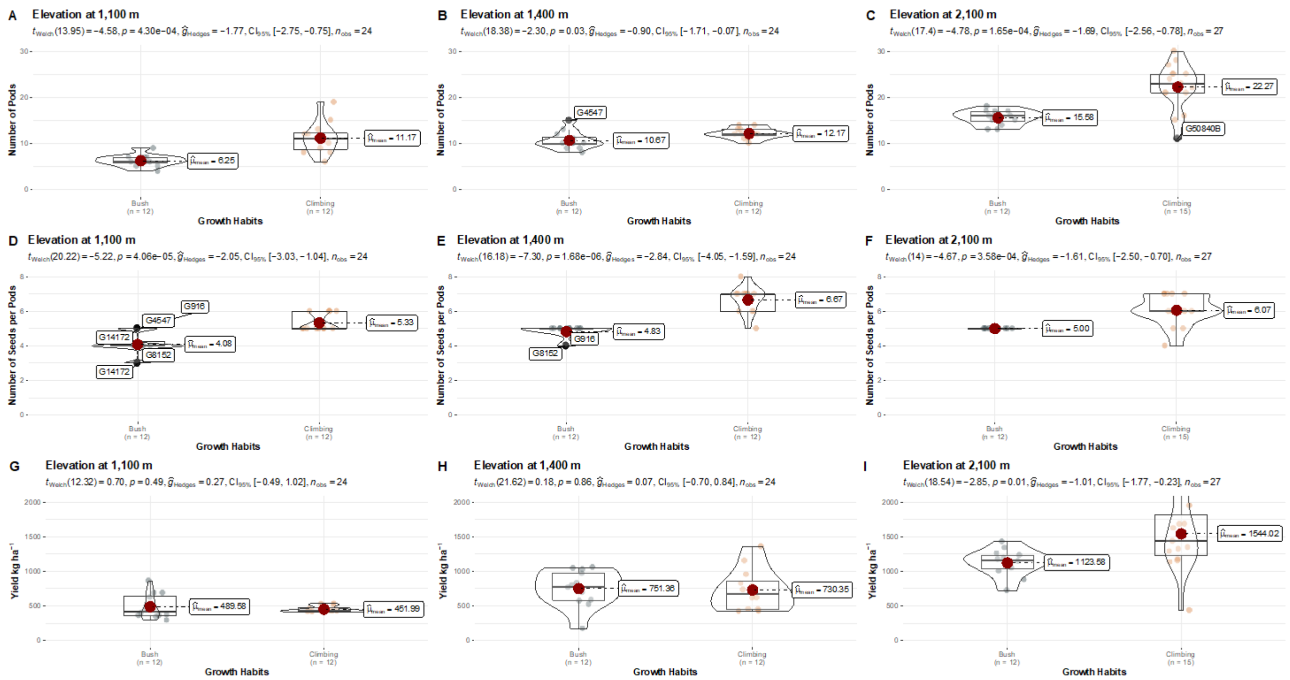

Figure 3. Yield components between growth habits across altitudes for each locally adapted accession of common bean (*P. vulgaris* L.) var. Liborino. Yield components were as follows: (**A**–**C**) number of pods, (**D**–**F**) average number of seeds per pod, and (**G**–**I**) average extrapolated yield. Altitudes are depicted as follows: (**A**,**D**,**G**) 1100, (**B**,**E**,**H**) 1400, and (**C**,**F**,**I**) 2100 m a.s.l. Colors of the dots indicate contrasting growth habits (grey for bush type and orange for climbers). Squared and rounded shapes mark boxplots and violin distributions, respectively. Selected accessions from the adaptation trials were considered in triplicate at the yield trials. Eight of nine accessions reached harvest across altitudes. Each subfigure's title depicts Welch's *t*-test, which is a parametric approach to compare combinations of groups when there is an imbalance in the number of individuals and homogeneity of variance cannot be assumed. When comparing yield across localities, average extrapolated yield was higher in AGROSAVIA's La Selva research station at 2100 m a.s.l. (1357.2 ± 459.4 kg ha^{-1}), followed by the trials in Liborina at 1400 m a.s.l. (740.9 ± 277.4 kg ha^{-1}) and 1100 m a.s.l. (470.8 ± 129.3 kg ha^{-1}, *p*-value = 1.1 × e^{-11}, Table 3).

Similar patterns to those for number of pods (Figure 3A–C) were found for average number of seeds per pod. Specifically, climbing bean accessions on average had more seeds per pod than bush types (6.0 ± 0.90 vs. 4.6 ± 0.6 for climbers and bush types, respectively, *p*-value = 3.6 × e^{-11}, Figure 3D–F). On average, pods had more seeds in AGROSAVIA's La

Selva research station at 2100 m a.s.l. (5.6 ± 0.8), followed by the trials in the two localities in Liborina at 1400 m a.s.l. (5.7 ± 1.1) and 1100 m a.s.l. (4.7 ± 0.9, p-value = 4.5 × e^{-04}).

However, no significant differences were found for average extrapolated yield between climbing bean accessions and bush types (957.6 ± 601.6 kg ha^{-1} vs. 788.1 ± 337.1 kg ha^{-1} for climbers and bush types, respectively, p-value = 0.13, Table 3, Figure 3G–I). We only found significant differences between climbing bean accessions and bush types in AGROSAVIA's La Selva research station at 2100 m a.s.l. (p-value = 0.01, Figure 3I).

Finally, as a combined measure of all yield components per genotype, climbing beans displayed average extrapolated yield ranging from 418.3 ± 3.0 kg ha^{-1} for G50840B at 1100 m a.s.l. to 1720.0 ± 588.4 kg ha^{-1} for G51018 at 2100 m a.s.l. Meanwhile, bush beans exhibited average extrapolated yield ranging from 362.1 ± 74.9 kg ha^{-1} for G14172 at 1400 m a.s.l. to 1169.4 ± 228.4 kg ha^{-1} for G8152 at 2100 m a.s.l. In terms of genotypes' ranking, average extrapolated yield was significantly higher for G4547 at 1100 m a.s.l., G50834 at 1400 m a.s.l., and G50834 at 2100 m a.s.l.

3.3. Participatory Breeding Evaluation

With a participatory approach, Liborino's farmers were involved in the assessment of the bean accessions following the adaptation trials in the first year. Farmers evaluated grain traits from two localities and compared them with the commercial genotype under multiplication. Among the climbing common bean var. Liborino genotypes tested in the yield trials, three accessions (G51433, G51018, and G50840B) fulfilled farmers' expectations in terms of seed coat color pattern and shape (Figure 4).

Figure 4. Farmers' preference (G50840B, **left**) in terms of seed coat color and rounded-squared seed shape from all accessions taken to yield trials, matching expectations of the commercial Liborino type (**right**). Squared shapes are likely a byproduct of dense seed packing within pods [22].

Finally, five kilograms of seed of common bean var. Liborino led to 253.5 kg of seed crop production with desirable quality. Optimum quality was assessed based on genetic factors (families with desired growth habit and flower color), abiotic resistance (visual inspection to assess symptoms for seed borne and virus diseases), and physiology (dry seed weight within ± 1g of the standard deviation, seed humidity < 14%, and >80% germination rate). Seed was delivered in February 2022 to 39 farmers, each receiving 6.5 kg of uniform seeds with the target quality described. Farmers were asked to use the same criteria (single-seed descendant monitoring) to maintain seed integrity in the long-term.

4. Discussion

Our trials reveal maximum average extrapolated yields up to 1169.4 ± 228.4 kg ha^{-1} for the bush types (G8152) and up to 1720.0 ± 588.4 kg ha^{-1} for the climbers (G51018), both at 2100 m a.s.l. A total of three climbing accessions matched farmers' expectations for seed coat color and shape, leading to 253.5 kg of seed delivery in 2022.

An unanticipated variation within the common bean var. Liborino genepool is the bush type, a growth habit lost *in situ* and only kept at the genebank. Farmers had historically reported climbing indeterminate growth habit for var. Liborino. However, the more precocious bush Liborino may prove appealing in regions with prolonged periods of drought [27,28], such as those found at the bottom of the Cauca river canyon.

Fewer days to flowering and shorter growing cycles (*ca.* four months) may equally enable three production cycles of bush Liborino beans per year, as compared to the two traditional annual cycles of the climbing beans. More crops per year may ultimately compensate the fewer number of pods and lower total yield of the bush type, and can avoid limited drought periods and other stresses increasingly influenced by climate change. Another benefit of the bush growth habit is that it does not require tutoring, reducing the production costs, and allowing for more efficient intercropping. Leveraging bush type Liborino cultivars would require quantifying in more detail its market annual worth, as well as the consumer's acceptability in the light of its narrower seed shape. After all, bush types did not match the seed shape of the commercial standard, likely because the shorter growing cycle limited the filling of the grains. Squared shapes have been attributed to denser seed packing within pods [22]. Seed coat color also tended to be more stable in the selected climbing accessions, despite naturally high levels of segregation in the pool of 44 accessions likely due to the landrace nature of the genotypes.

In general, screening agronomic yellow bean diversity, including Liborino's, is a key step to unleashing innovative pre-breeding quality attributes beyond yield components. For instance, yellow beans' low contents of tannins, insoluble dietary fiber, and indigestible proteins [14], may decrease flatulence and ease digestibility in novel consumer markets unaccustomed to daily bean ingestion. Similarly, the fast cooking time of yellow beans may offer an advantage in areas where cooking fuel is an expensive or inaccessible commodity [13]. Lower concentrations of polyphenolic compounds in yellow seed coat color beans [15] may even facilitate iron bioavailability [16] and biofortification of undernourished communities. This way, plant breeding tends from a yield-centered perspective [29] into diversified [30], adaptive [31,32], and quality [33,34] targets.

Meanwhile, genetic quality assurance during seed multiplication ensures high quality common bean seeds are delivered to farmers. This adds to recent efforts to characterize and disseminate local agrobiodiversity [35,36]. A research-industry consortium held in 2016–2018 by a local NGO (HTM, Medellín), Instituto von Humboldt (Bogota, Colombia) and EPM (the main energy service company in Colombia) identified Liborino common bean as a sustainable economic alternative for growers in the territory impacted by the Hidroituango Hydroelectric dam [25], the largest in South America [37]. In this isolated region of the Cauca river canyon, illegal mining [24], civil conflict and illicit crops [23] had only been partially hampered thanks to the recent "Agreement to End the Conflict and Build Peace" in Colombia [38]. However, socio-economic instability is still high in the territory, and relapse of illegal mining and crops is likely to happen [24].

Effective utilization of agrobiodiversity [39], including Liborino bean, should as well harness parallel creative strategies to improve its impact. In addition, the transfer of technology focused on the production of quality seed as a process integrated into plant breeding programs contributes to the conservation and use of cultivars by farmers. Short-term knowledge and technology transfer to farmers, technicians and local institutional leaders, would also help guarantee long-term sustainable domestic seed production, a major bottleneck in the supply chain to ensure seed quality [26]. In the middle term, Liborino bean may be susceptible to Geographical Indications such as a "Collective Trademark" or an "Appellation of Origin", encouraging its marketability [40].

Our work further encourages the implementation of next-generation genomic tools to accelerate the screening of promising genotypes of Liborino yellow beans. As a result, it will reduce the time needed for adapted elite varieties to reach the farmers, contributing to the food and nutritional security [41] of the local population in the Cauca river canyon, while stabilizing the so far segregating seed coat color pattern within some accessions. In parallel, next-generation genetic tools and molecular breeding [42] should be merged with local expertise on participatory plant breeding and seed multiplication [43].

This inter-disciplinary pipeline will serve boosting research capacity in the region, so that new knowledge, genotypes and practices are successfully uptake, maintained and scaled [44]. Long term partnerships with NGOs and municipal technology transfer offices will enable efficient delivery of promising adapted Liborino bean genotypes to farmer communities, and an effective tracing of their adoption [45] and impact [46].

We envision these various actors converging across the middle Cauca river territory in order to concert initiatives that contribute generating within five to ten years a positive impact on the most marginalized communities such as victims of the conflict, displaced families and undernourished native communities [38], all of which are currently being affected by the construction of the Hidroituango Hydroelectric dam [25]. Improved genetic resources such as Liborino yellow bean will ultimately stimulate food security [41] and the economical maturity of these rural communities, as part of a broader Colombian bioeconomy strategy [47] to assess, conserve and utilize crop and wild [47,48] agrobiodiversity in the service of (1) exotic parental section [49] for interspecific hybridization schemes [50,51], (2) conservation of local [52] environmental adaptation [53], allelic and haplotype diversity [54] and broad climate change thermal responses [55], and (3) sustainable agricultural development [56].

5. Conclusions

This work has ensured seed quality for common bean var. Liborino, a yellow Andean common bean known for its apparent high digestibility and adaptation to the local conditions in the northwest Andes of Colombia, yet eroded after decades of suboptimal propagation. After six field trials for adaptation and yield performance, in parallel to seed uniformity and multiplication protocols started in 2020, average extrapolated yields ranged up to 1169.4 ± 228.4 kg ha^{-1} for the bush types (G8152) and up to 1720.0 ± 588.4 kg ha^{-1} for the climbers (G51018), both at 2100 m a.s.l. A total of 253.5 kg of uniform seeds were delivered to 39 farmers in 2022, matching farmers' expectations for seed coat color and shape. This vertically integrated breeding strategy is expected to boost Liborino commercialization, positively impacting the sustainable economic development of the rural communities in the Cauca river canyon. The seed multiplication pipeline standardized for Liborino bean could as well be extended to other promising bean landraces conserved *in situ* at isolated pockets of cryptic diversity.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12102285/s1, Figure S1: seed coat color patterns across the 44 tested accessions of Liborino common bean (*Phaseolus vulgaris* L.), G identifiers follow CIAT's genebank; Figure S2: days to harvest at the yield trials across altitudes for each locally adapted accession of Liborino bean. Selected accessions from the adaptation trials were considered in the yield trials. Differentially filled bars mark contrasting growth habits; Table S1: Passport data of 44 Liborino type common beans (*Phaseolus vulgaris* L.) used in this study with data presented based on the International Center for Tropical Agriculture (CIAT-Bioversity) genetic resources unit (data downloaded on 11 May 2022).

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