resources

MDPI

Article

Impact of Altitudinal Gradients on Exportable Performance, and Physical and Cup Quality of Coffee (*Coffea arabica* L.) Grown in Inter-Andean Valley

Katia Choque-Quispe [1,*], Delma Diana Reynoso-Canicani [1,*], John Peter Aguirre-Landa [2], Henrry W. Agreda Cerna [2], Medalit Villegas Casaverde [2], Alfredo Prado Canchari [2], Edwin Mescco Cáceres [2], Lucero Quispe Chambilla [3], Hilka Mariela Carrión Sánchez [3], Yasminia Torres Flores [4], Henry Palomino-Rincón [4] and David Choque-Quispe [4]

[1] Accounting and Finance Academic Department, José María Arguedas National University, Andahuaylas 03701, Peru
[2] Business Administration Academic Department, Universidad Nacional José María Arguedas, Andahuaylas 03701, Peru; jpaguirre@unajma.edu.pe (J.P.A.-L.); hagreda@unajma.edu.pe (H.W.A.C.); mvillegas@unajma.edu.pe (M.V.C.); aprado@unajma.edu.pe (A.P.C.); emescco@unajma.edu.pe (E.M.C.)
[3] Food Engineering Academic Department, Intercultural de Quillabamba National University, Quillabamba 08741, Peru; lucero.quispe@uniq.edu.pe (L.Q.C.); hilka.carrion@uniq.edu.pe (H.M.C.S.)
[4] Agroindustrial Engineering Academic Department, Universidad Nacional José María Arguedas, Andahuaylas 03701, Peru; torres7yasminia@gmail.com (Y.T.F.); hpalomino@unajma.edu.pe (H.P.-R.); dchoque@unajma.edu.pe (D.C.-Q.)
* Correspondence: kchoque@unajma.edu.pe (K.C.-Q.); dreynoso@unajma.edu.pe (D.D.R.-C.)

Abstract

Coffee production is one of the main sources of income for products from Peru's inter-Andean valleys. However, the rugged geographical conditions offer few growing areas with different altitudes, which could lead to variations in the quality of the beans and, consequently, of the coffee in the cup. This study aimed to evaluate the effect of altitudinal gradients on the exportable yield, and physical and cup quality of the Typica and Catimor varieties produced in the Inkawasi inter-Andean valley of Cusco, Peru. Coffee beans produced at altitudes of 1600, 1800, and 2100 m were considered, and the physical quality of parchment and green coffee was evaluated using Peruvian Technical Standards and the SCAA guidelines. Similarly, the sensory attributes of the coffee in the cup were assessed according to criteria established by the SCAA by five certified tasters. It was observed that increasing altitude considerably reduces pest attack and damage in both varieties and increases secondary damage, shrinkage, and exportable yield, which ranged from 79.12 to 81.98%. Sensory attributes ranged from "Very Good" to "Extraordinary", allowing the Specialty Grade (>80 points) to be achieved according to SCAA standards. The PCA revealed that the Typica variety has superior sensory qualities that improve with altitude. The coffee produced in the Inkawasi valleys is well received on the international market, especially that grown above 1800 m. Its sustainable cultivation could improve the socioeconomic conditions of its inhabitants.

Keywords: sensory attributes; shrinkage; Typica and Catimor varieties; parchment coffee; green coffee; secondary and primary damage

check for updates

Academic Editor: Benjamin McLellan

Received: 23 July 2025
Revised: 23 August 2025
Accepted: 26 August 2025
Published: 30 August 2025

Citation: Choque-Quispe, K.; Reynoso-Canicani, D.D.; Aguirre-Landa, J.P.; Agreda Cerna, H.W.; Villegas Casaverde, M.; Prado Canchari, A.; Mescco Cáceres, E.; Quispe Chambilla, L.; Carrión Sánchez, H.M.; Torres Flores, Y.; et al. Impact of Altitudinal Gradients on Exportable Performance, and Physical and Cup Quality of Coffee (*Coffea arabica* L.) Grown in Inter-Andean Valley. *Resources* **2025**, *14*, 136. https://doi.org/10.3390/resources14090136

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

In the global coffee market, the primary factor determining a customer's purchasing decision is bean quality, associated with cup quality, for example, aroma, flavor, body,

acidity, and consistency. Quality is determined by the set of physical and organoleptic characteristics that motivate a buyer to pay a differentiated price for the product, which represents better income and profitability for the farmer [1,2]. Non-compliance with coffee quality requirements affects not only coffee growers in terms of income but also the coffee production chain [3–5].

Peru has diverse ecological zones with varied climates that allow the cultivation of products throughout the year, in comparison to other latitudes in the world. This geographical characteristic gives Peru the advantage of being able to offer the international market fresh and organic coffee between the months of April and August, a time when coffee beans from Central America and Mexico are scarce [6–8]. Peru produces coffee of the Typica (60%), Caturra (15–20%), Catimor (10–15%), and Bourbon (5–8%) varieties in 32 microclimates between 900 and 2000 m altitude, occupying ninth place in terms of world production (220,000 tons in 2024) and being the second largest exporter of organic coffee, showing an increase of approximately 19% during the last 5 years [8,9].

Coffee is the first agro-exportable product, involving more than one million Peruvians who live directly and indirectly from the coffee activity, providing economic support to a significant number of families who are responsible for its cultivation, harvesting, transportation, primary processing, industrialization, and marketing, thus promoting rural employment and local and regional development [5,9–12].

The inhabitants of the Inkawasi district of Cusco, Peru, have increased their coffee production over the past 10 years, making it one of their main economic activities for family sustenance. This district has a favorable climate and conditions for the production of specialty coffees. Its geographical characteristics of very rugged terrain with steep slopes, ranging from 1600 to 2500 m of altitude, do not allow the implementation of mechanized technologies in coffee production, in addition to having reduced areas for the cultivation of specialty coffees. This non-massified cultivation produces coffee with unique flavor, aroma, acidity, body, and consistency, along with organic production. This allows exporting companies to engage in direct trade with farmers or their associations, establishing long-term contracts and offering higher prices than those of the local market. However, their products are often rejected due to quality variability caused by different cultivation gradients.

On the other hand, producers in the inter-Andean valleys of Peru have formed parchment and green coffee cooperatives because their products are in high demand and meet the requirements of the international and exportable markets. However, there are still challenges to overcome, such as crop conditions and pest management, that directly affect the quality of the beans and cup.

One of the pests that causes significant economic and product losses is coffee rust (*Hemileia vastatrix*). Therefore, farmers have opted to replace their traditional coffee plantations with varieties more resistant to this disease. However, another problem with these varieties is that their cup profiles tend to be of lower quality compared to non-resistant varieties. Given this, cultivation has been tested in places with altitudes greater than 1800 m, where this pest has less effect; although production yield and size decrease, its sensory aspects are advantageous.

Therefore, a physical and sensory evaluation was carried out on two coffee varieties, one resistant to rust (Typica variety) and one not resistant to rust (Catimor variety), which were grown at different altitudes. For the sensory evaluation, expert coffee tasters were selected according to the SCAA's methodology. These results will enable coffee producers to cultivate land at an optimal altitude and increase their exportable coffee yield.

2. Materials and Methods

2.1. Raw Materials and Crop Field Characteristics

The parchment coffee of the Typica and Catimor varieties was supplied by the San Fernando Cooperative, located in the Inkawasi district, Cusco, Peru. The beans were grown and harvested at 1600, 1800, and 2100 m altitude, on lands with coordinates 13°15′15″ S–73°18′47″ W, 13°15′03″ S–73°17′47″ W, and 13°14′30″ S–73°17′48″ W, respectively (Figure 1), in the period 2022–2023. The Typica variety cultivated at 1600, 1800, and 2100 m altitude was coded as T1600, T1800, and T2100, respectively, and Catimor was coded as C1600, C1800, and C2100.

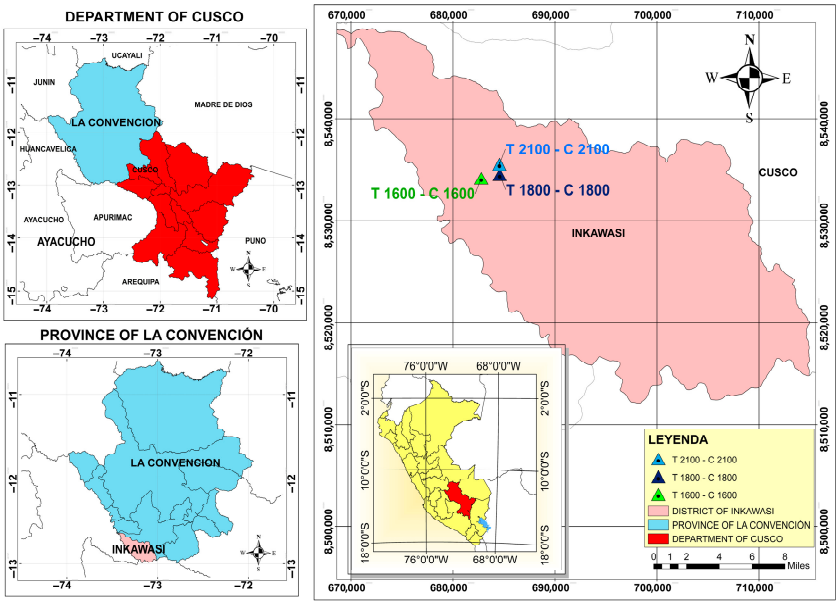

Figure 1. Crop field locations.

The Inkawasi district is situated in an inter-Andean valley in Peru, characterized by temperatures ranging from 8 to 35 °C, relative humidity between 60% and 80%, annual rainfall between 600 and 800 mm, and a Köppen Cwb classification. The area is rugged and hilly, with steep slopes, and cultivation areas where intensive technology cannot be applied, where traditional, ancestral hand cultivation prevails. The croplands have loam and loam/clay/sand soil characteristics (Table 1).

Table 1. Coffee growing soil characteristics in the altitudinal gradients.

Sample	pH (1:1)	EC (1:1) (µS/cm)	$CaCO_3$ (%)	OM (%)	P (ppm)	K (ppm)	Composition				CEC	Ca^{2+}	Mg^{2+}	K^+	Na^+	$Al^{3+} + H^+$
							Sand (%)	Silt (%)	Clay (%)	Texture	meq/100 g					
1600	6.61	280	0.00	4.71	18.24	191	46	30	23	L	21.02	16.21	1.44	0.57	0.19	0.04
1800	6.56	310	0.00	4.88	20.3	185	45	32	23	L	20.00	15.20	1.38	0.53	0.17	0.00
2100	5.53	170	0.00	5.52	13.7	136	51	26	23	L.C.S.	18.08	9.78	1.52	0.42	0.15	0.10

Abbreviations: L—loam, C—clay, S—sand.

2.2. Physical Quality of Parchment Coffee

The humidity was determined using a humidity meter (model G600i, Gehaka, São Paulo, SP, Brazil). First, 350 g of parchment coffee was taken, the husk was removed to obtain the green coffee, then it was sieved through meshes from 0 to 20, and the weights retained in each mesh were noted. The observable defects of green coffee that exceeded mesh No. 14 were identified using criteria of the Peruvian technical standards NTP 209.310.2019 [13], while those less than or equal to mesh No. 12 were discarded. Primary defects (full black, full sour, dried cherry, fungus damage, foreign matter, severely berry

borer) and secondary defects (partial black, partial sour, parchment, floating/bleached, immature bean, withered bean, shell, broken/chipped/cut, husk, and slight berry borer) were considered.

2.3. Exportable Yield Determination

The exportable yield is an important indicator of the quality and efficiency of the production process, revealing the profitability and commercial competitiveness of a coffee in the international market. Values > 80% indicate excellent yield (very good processing and selection of the coffee); between 75 and 79% indicates good yield (exportable without problems); between 70 and 74% is considered acceptable, with losses (possible defects or bad processing); and <70% indicates low yield, possible bad selection, and the presence of many defects [14]. The exportable yield was determined according to Equation (1).

$$EY = 100 - parchment\ coffee\ husks\ (\%) - Discard\ (\%) - defects\ (\%) \quad (1)$$

2.4. Preparation of Coffee in Cup

Gold coffee beans were roasted one day before cupping. First, 100 g was taken, retained in 14 and 18 mesh, and roasted at 185 °C for an interval of 10 min in a drum roaster. The samples were then cooled at room temperature, continuously stirred, and subsequently packed in HDPE bags and stored for 8 h before cupping [13,15].

In 200 mL glass beakers, 11 g of roasted coffee was placed and ground. They were then covered to prevent the loss of volatile compounds and the room from becoming saturated with odors. The fragrance and aroma of the ground coffee were then tasted immediately afterward. The maximum tasting time was no more than 15 min. The tests were performed in triplicate.

2.5. Preparation of Drinkable Coffee

Potable water (pH 7.8, hardness 120 ppm, turbidity 0.0 NTU, conductivity 80 µS/cm, residual chlorine 0.0 ppm) was used and brought to a boil (approximately 85 °C). Then, 11 g of ground coffee was added in a coffee/water ratio of 1:5.5. The tasting was carried out for flavor, aftertaste, acidity, body, balance, clean cup, and sweetness [13].

2.6. Coffee Cupping

This was carried out by a panel of five cuppers in triplicate, trained in the Quality Control Laboratory of San Fernando Agrarian Coffee Cooperative Ltd., Inkawasi, Cusco, Peru. The methodology developed by the Specialty Coffee Association of America was followed [13,15].

2.7. Statistical Data Processing

Data were collected in triplicate and represented with descriptive statistics. The normal distribution of the data was verified using the Shapiro–Wilk test (0.7874) with 5% significance. One-factor ANOVA and Tukey's test were applied. Multivariate PCA and Pearson's correlation (with hypothesis testing using Student's *t*-test) at 5% significance were also applied. Excel spreadsheets and OrginPro 2025 software were used.

3. Results and Discussion

3.1. Physical Properties of Parchment and Green Coffee

The moisture of coffee parchment was measured and found to range from 9.09 to 9.13% for the Typica variety and from 8.52 to 9.02% for Catimor, while for green coffee, values between 8.47 and 9.03% were reported (Table 2). These levels are below the standards set by the SCAA, which indicates a high risk of flavor and aroma loss due to the volatilization

of aromatic compounds. Additionally, these levels can cause coffee to break easily during handling and transportation, and from a commercial perspective, they affect weight and reduce processing yield.

Table 2. Physical characteristics of parchment and green coffee.

Variety	Parchment Coffee Moisture (%)				Husk or Shrinkage (%)				Defects (%)				Discard (%)				Green Coffee Moisture (%)			
	$\bar{x}$	±s	CV	*	$\bar{x}$	±s	CV	*	$\bar{x}$	±s	CV	*	$\bar{x}$	±s	CV	*	$\bar{x}$	±s	CV	*
T1600	9.11	0.025	0.28	a	16.22	0.16	1.00	c	1.39	0.27	19.21	a	0.41	0.11	27.61	d	9.03	0.06	0.64	a
T1800	9.13	0.029	0.32	a	17.13	0.22	1.26	b	0.68	0.06	9.21	b	0.86	0.13	14.95	a	8.93	0.06	0.65	a
T2100	9.09	0.036	0.40	a	17.40	0.09	0.52	b	0.63	0.11	17.80	b	0.82	0.17	20.84	b	8.63	0.06	0.67	b
C1600	8.94	0.067	0.75	a,b	17.06	0.09	0.51	b	1.48	0.23	15.29	a	0.25	0.05	20.00	e	8.97	0.12	1.29	a
C1800	9.02	0.029	0.32	b	17.46	0.19	1.09	b	1.84	0.26	13.93	a	0.21	0.07	34.64	e	8.93	0.12	1.29	a
C2100	8.52	0.076	0.90	c	18.67	0.29	1.55	a	1.55	0.19	12.18	a	0.67	0.07	10.83	c	8.47	0.06	0.68	b

Abbreviations: $\bar{x}$—mean, s—standard deviation, CV—coefficient of variability. * Evaluated using Tukey's test at 5% significance.

These low values are associated with climatic conditions, primarily relative humidity. Values below 60% significantly influence the loss of moisture in the coffee bean. Storage temperatures above 30 °C and humidity levels between 50 and 60% do not allow the bean to reach a moisture content above 10% [16–18]. However, high humidity levels above 12% make the bean susceptible to the presence of ochratoxins [19].

Regarding the shrinkage, measured as the amount of husk resulting after the threshing of parchment coffee, values ranging from 16.22 to 18.67% were observed, while defects were found between 0.63 and 1.84%, although they are lower than the reference values established in NTP 209.310:2019 [13], which is 18% for shrinkage and 5.5% for defects. The Catimor variety, which results from hybridization between Arabica and Robusta, showed higher values due to its thicker skin and increased resistance to pests, which may lead to a larger proportion of skin remaining after threshing [20]. Conversely, the discard, which considers beans smaller than 12 mesh, was higher for the Typica variety, although the values observed were less than 0.17%, indicating uniformity of the beans in both varieties.

3.2. Primary and Secondary Defects

In coffee production, altitude or gradient is a crucial factor influencing green bean quality and susceptibility to damage or defects. For primary defects, such as full black, full sour, dried cherry, and foreign matter, no evidence was observed for the two varieties at the three altitudinal levels (Figure 2a). However, the damage caused by fungus damage is evident at lower altitudes for both varieties. This is likely due to climatic conditions, such as higher relative humidity and ambient temperature [21].

Meanwhile, the presence of severely berry borer was greater at 1800 m altitude for both varieties and was present in the crops of the Catimor variety. This was due to agronomic management, including late harvest, presence of ripe/overripe fruits on the plant, and the loss of natural biological controllers, affecting the coffee beans in terms of lower weight, lower density, increased loss in threshing, decreased exportable yield, and so on. However, in the coffee cup, they produce earthy, bitter, or insect flavors, with loss of sweetness and acidity [21,22]. In other words, severe CBB damage occurs due to optimal conditions for its reproduction, such as low altitudes, high humidity, poor harvesting, and deficient management.

Regarding secondary damage, it can be observed that it increases slightly with altitude in both varieties (Figure 2b). Regarding beans with partial black and partial sour, it occurs more frequently in the Catimor variety and increases with higher altitude. This could be due to poor post-harvest handling, prolonged fermentation [23], harvesting of overripe or damaged fruits, and excess humidity during drying, generating phenolic, vinegary, moldy, and unbalanced acidity flavors in the coffee cup. This behavior is characteristic of the Catimor variety, due to its hybrid nature and its low adaptability to local conditions.

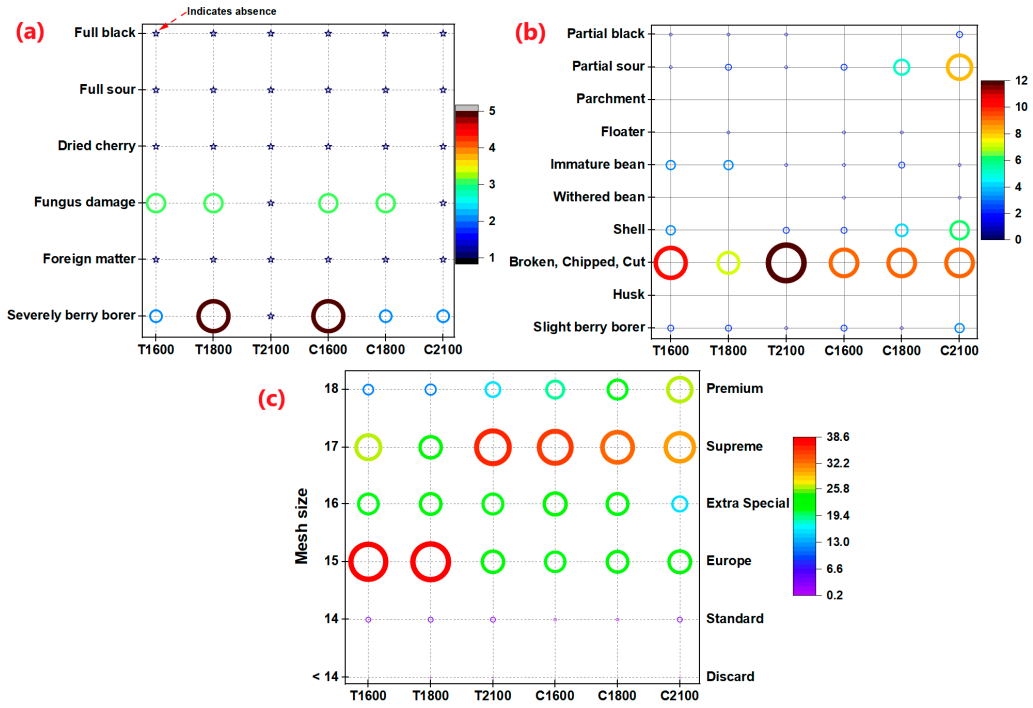

Figure 2. (**a**) Primary coffee damage *; (**b**) secondary coffee damage *; (**c**) coffee bean size *. * Different colors indicate different attribute values, while the size of the circles indicates intensity (larger circles indicate greater intensity or higher values).

Immature beans are observed in both varieties and increase with altitude. Their presence is mainly due to premature harvesting, water stress, nutritional deficiencies (N, B, Zn), and excessive shading. This defect causes low green kernel density, an opaque color, and low sugar content, which can lead to a vegetal, astringent, and unpleasant taste in the cup, with little body and sweetness.

On the other hand, withered bean occurs mainly in the Typica variety, which can cause loss of body and flat flavor in the cup. This defect is mainly due to the lack of water during physiological growth.

The Catimor variety shows a greater presence of shells at higher altitudes, although Typica is present at 1600 m. This indicates that these beans are more susceptible to carbonization during coffee roasting, which would lead to poor aroma development and body in the cup. While broken, chipped, and cut beans are mainly due to mechanical breakage due to low density or inadequate threshing, it was the most frequent and major damage in the two varieties, which would cause irregular roasting of the coffee.

3.3. Bean Size

The size of green coffee beans in the studied varieties (Typica and Catimor) is influenced by several factors, such as altitude, agronomic practices, and physiological characteristics. These factors not only affect the physical characteristics of the beans but also their quality in the cup. It was observed that altitude has a considerable influence (Figure 2c), due to the thermal and climatic conditions of the environment, which would cause greater accumulation of secondary metabolites and cellular expansion of the endosperm [24]. Therefore, both varieties at lower altitudes have bean sizes larger than 14 mesh, with a classification between Europe and Supreme.

Likewise, the characteristics of the crop soils are crucial for the development of good-sized beans, so the high content of organic matter, phosphorus, and magnesium (Table 1) could contribute to this effect. However, agronomic practices such as nutrient dosage,

micronutrients, pest control, and harvesting are critical for the production of healthy, strong, and good-sized crops, ensuring sensory quality, which contributes to export quality [25].

3.4. Exportable Performance

It was observed that the Typica variety exhibited a higher exportable performance (>81.15%), which decreased significantly with altitude, a trend also noted, albeit to a lesser extent, in Catimor (Table 3). Although the number of defects is lower with altitude for Tipica at 2100 and higher for Catimor, the grade of the green bean corresponds to 1, that is, less than 15 defects [14]. This result guarantees the highest international standards and the commercial quality of the green beans produced in the Inkawasi valleys. Although T1600 vs. C2100 would represent a significant economic impact on a commercial scale.

Table 3. Grade and exportable performance of green coffee.

Variety	Defect Score	Grade	Exportable Performance (%)			
			$\bar{x}$	±s	CV	*
T1600	4	1	81.98	0.42	0.51	a
T1800	4	1	81.33	0.04	0.05	a, b
T2100	2	1	81.15	0.11	0.13	b, c
C1600	4	1	81.21	0.16	0.20	b
C1800	4	1	80.49	0.34	0.42	c
C2100	5	1	79.12	0.20	0.26	d

Abbreviations: $\bar{x}$—mean, s—standard deviation, CV—coefficient of variability. * Evaluated using Tukey's test at 5% significance.

It has been observed that green coffee produced on a Colombian farmhouse achieved performance levels of around 94%, which makes a significant contribution to its GDP. However, Ecuador's coffee exports faced challenges due to high production costs and low productivity, and coffee sales contributed only 0.7% of the national GDP [26–28]. In comparison to the results obtained in the present study, it is expected that although the yields are acceptable, they could be improved through the application of strategies such as training in marketing and the adequate use of financing to strengthen the production and export processes of coffee produced mainly in farms or small producers [29,30]. These criteria have been applied in countries such as Brazil and Mexico, which have considerably improved competitiveness in international coffee markets [24,31].

3.5. Sensory Quality of Coffee in the Cup

Sensory quality in the cup constitutes the second fundamental component in characterizing the exported coffee product, requiring consistency and distinctive organoleptic characteristics of the origin. This results from the relationship between botanical, geographic, climatic, and soil factors, not to mention agronomic practices, post-harvest processing, storage, transportation, roasting, and final preparation [32,33].

According to the SCAA [15], the coffee sensory attribute scores are classified as Good (6.00 to 6.75), Very Good (7.00 to 7.75), Excellent (8.00 to 8.75), and Extraordinary (9.00 to 10.00). The evaluated attributes reported scores between 7 and 10, ranging from Very Good to Extraordinary (Figure 3a). The attributes of sweetness, clean cup, and uniformity showed the highest scores for both varieties, meaning the coffee produced in Inkawasi would present natural sugars with no perceptible defects during the cupping replicas.

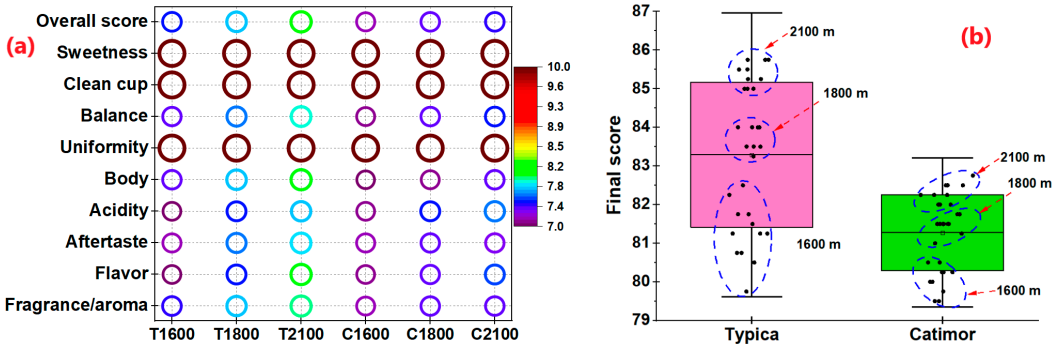

Figure 3. (**a**) Sensory attribute scores for cupped coffee; (**b**) final cupped coffee score.

Fragrance/aroma, flavor, residual flavor, acidity, body, balance, and overall score attributes, showed scores of around 8 for the Tipica variety grown at 1800 and 2100 m (T1800 and T2100), suggesting that the cupped coffee from these beans presents clear and defined expression of these attributes, with well-integrated characteristics, perceptible complexity, and cleanliness. Likewise, the acidity is bright and harmonious, with a creamy and structured body, with an aroma and flavor of floral and fruity notes. While T1600 and Catimor (C1600, C1800, and C2100) showed moderate expression and a certain simplicity, nevertheless, this level meets the minimum standards of specialty coffee without outstanding differentiating characteristics.

The results suggest that coffee produced in the Inkawasi valleys can be considered a specialty coffee (Specialty Grade), since it obtained a final score greater than 80 points for both varieties (Figure 3b), and a maximum of five defects (between primary and secondary) (Table 3). However, these attributes improve with altitudes above 1500 m, due to agroecological factors and the presence of microclimates with colder temperatures and longer exposure to sunlight that contribute to reduced growth rates [34,35]. Likewise, the composition of the soil is a determining factor in the development of coffee beans, having a significant impact on the sensory attributes. Thus, it has been observed that at higher altitudes, the soils contain multiple essential nutrients and organic matter that promote better flavor development [25,36,37].

These aspects favor the development of chemical and biological compounds that intensify the desirable attributes of coffee, such as bright acidity, sweetness, complex aromas, and balanced body [38,39]. This is attributed to a slower maturation of coffee cherries, which allows for more developed flavor profiles because they affect the chemical composition of the coffee beans, increasing fatty acids and decreasing certain alkaloids and chlorogenic acids, which can enhance sweetness and caramel notes in the cup [40–42].

3.6. Multivariate Analysis of the Physical and Sensory Quality of Coffee

The correlational analysis showed that the sensory attributes of coffee in the cup had a high correlation, indicating agreement among the tasters, which supports the evaluation (Figure 4a). Conversely, it was observed that an increase in the number and score of defects and the humidity of green coffee significantly reduces the quality of the cup. Another factor to consider is that export performance shows a weak relationship with the physical parameters of green coffee and the sensory attributes of the brewed coffee, suggesting a slight uniformity of these qualities with the altitude of cultivation for both varieties.

The relationship between the physical aspects of green coffee and the sensory attributes of coffee in the cup presents different complex edges, although it has been considered in several studies that the larger bean size influences the generation of more desirable flavors [43].

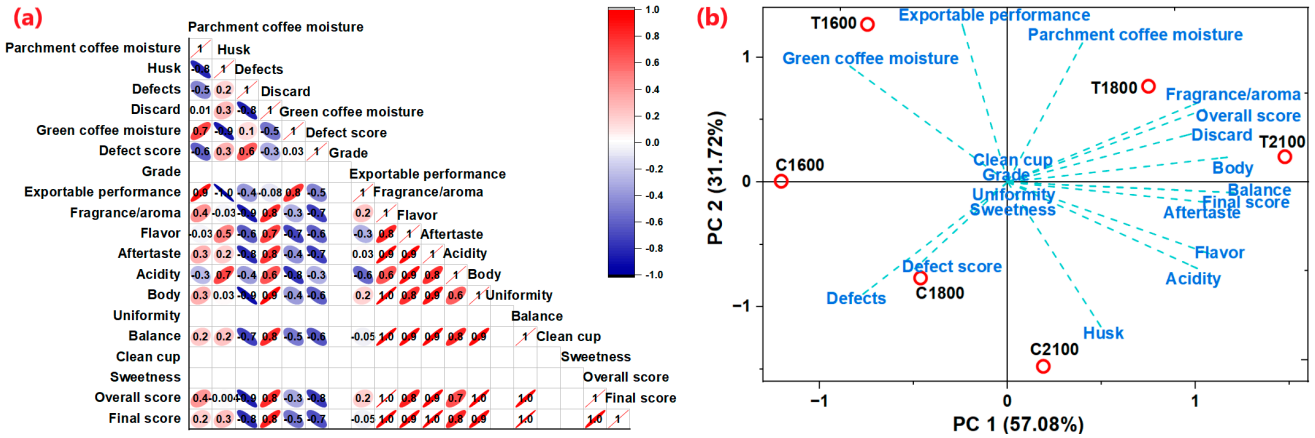

Figure 4. (**a**) Correlogram of the physical and sensory quality of coffee; (**b**) PCA for the physical and sensory quality of coffee based on altitudinal floors.

Similarly, primary and secondary defects have a negative impact on sensory notes [44]. Likewise, adequate moisture levels and high bean density have a significant influence on cup coffee attributes, mainly aroma, flavor, and aftertaste [45,46]. However, despite the relationship between the physical parameters of coffee beans and sensory attributes, the subjectivity and experience of tasters and consumers, in addition to the preparation of the coffee in the cup, must be taken into account.

The PCA, on the other hand, revealed that the total variability explained by PC1 and PC2 was 88.0% (Figure 4b), indicating good representativeness. It shows that the Typica variety performs better in sensory attribute qualities with increasing altitude, while the Catimor variety appears to be more affected by husk and defects, and that these issues increase with altitude, although beans grown at 2100 m altitude still possess relatively good sensory quality.

Another aspect to consider in the quality of coffee beans and coffee in the cup is the ambient temperature in the fields, which is closely related to geographical conditions. As altitude increases, the temperature decreases significantly, resulting in better bean quality, more complex acidity and aroma, and specialty coffees. Although higher growing temperatures result in higher yields, as observed in this study, the beans are prone to pests and low sensory quality [47–49].

These findings suggest that coffee growers should place greater emphasis on growing coffee varieties above 1800 m. Many inter-Andean valleys in Peru, due to their geographical characteristics, present this condition. Based on this study, coffee cooperatives should join forces and expand their cultivation areas in gradients between 1800 and 2100 m, to guarantee the physical and cup quality of the coffee, taking into account aspects such as sustainable agriculture, circular economy, and responsible management of forests and wildlife areas.

4. Conclusions

Coffee, a bean in high demand due to its sensory qualities, presents differences in its physical and cup characteristics, influenced by the variety and, above all, by different altitudes of cultivation floors, which is related to the economy of the local producer and the GDP of the producing countries. This study showed that low humidity levels in parchment and green coffee for the Typica and Catimor varieties are influenced by climatic conditions and that damage due to pests decreased considerably with increasing altitude. Likewise, the secondary damage studied increases with the altitude of the crop and has a significant negative impact on the physical quality of the coffee, with more emphasis on the Catimor

variety, which considerably affects the commercial performance, although it reported values ranging from 79.12 to 81.98%, which would have a significant economic impact on a commercial scale for producers in the Inkawasi area. On the other hand, it was observed that the sensory attributes are between "Very good" and "Extraordinary", highlighting sweetness, cleanliness, uniformity, bright acidity, balanced body, and complex flavors, which allows it to reach the Specialty Grade category (>80 points) according to SCAA standards, with superior sensory attributes in Typica variety beans grown over 1800 m. Climatic factors, microclimates, and soil quality considerably influence the organoleptic profile of coffee beans. The Typica variety adapts to altitudes, offering good qualities, and can be called "high-altitude coffee", although the Catimor variety responds best to altitudes of 2100 m. The altitude or gradient is a determining factor in the quality of coffee, although aspects such as water quality, mineral content, and microorganisms are critical and require attention from producers and competent entities.

Author Contributions: Conceptualization, D.C.-Q.; D.D.R.-C., K.C.-Q. and Y.T.F.; methodology, K.C.-Q., J.P.A.-L., H.W.A.C. and Y.T.F.; software, D.C.-Q.; validation, E.M.C., L.Q.C., H.W.A.C. and H.M.C.S.; formal analysis, A.P.C., M.V.C., H.P.-R. and D.C.-Q.; investigation, K.C.-Q., D.D.R.-C., J.P.A.-L., H.W.A.C., E.M.C., L.Q.C., H.M.C.S., Y.T.F. and H.P.-R.; resources, M.V.C. and A.P.C.; data curation, D.D.R.-C. and Y.T.F.; writing—original draft preparation, K.C.-Q., D.D.R.-C., Y.T.F. and D.C.-Q.; writing—review and editing, K.C.-Q., D.D.R.-C., J.P.A.-L. and D.C.-Q.; visualization, H.W.A.C., M.V.C. and D.C.-Q.; supervision, D.C.-Q.; project administration, K.C.-Q. and D.D.R.-C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: Data can be requested from the authors.

Acknowledgments: The authors thank the Cooperativa Agraria Cafetalera-CAC San Fern ando del Distrito de Inkawasi, Cusco, Peru, as well as the Universidad Nacional José María Arguedas de Andahuaylas and the Universidad Intercultural de Quillabamba, Peru.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Paterek, R.; Geoghegan, S.; Creaven, B.S.; Power, A. Coffee: Lighting Its Complex Ground Truth and Percolating Its Molecular Brew. *Beverages* **2024**, *10*, 119. [CrossRef]
2. Freitas, V.V.; Borges, L.L.R.; Vidigal, M.C.T.R.; dos Santos, M.H.; Stringheta, P.C. Coffee: A comprehensive overview of origin, market, and the quality process. *Trends Food Sci. Technol.* **2024**, *146*, 104411. [CrossRef]
3. Garcia, A.; Dávila, J.; Wong, L. Framework to improve the traceability of the coffee production chain in peru by applying a blockchain architecture. In Proceedings of the 2022 32nd Conference of Open Innovations Association (FRUCT), Tampere, Finland, 9–11 November 2022; pp. 93–101.
4. Gois, T.C.; Thomé, K.M.; Balogh, J.M. Behind a cup of coffee: International market structure and competitiveness. *Compet. Rev. Int. Bus. J.* **2023**, *33*, 993–1009. [CrossRef]
5. Rubio-Jovel, K. Coffee production networks in Costa Rica and Colombia: A systems analysis on voluntary sustainability standards and impacts at the local level. *J. Clean. Prod.* **2024**, *445*, 141196. [CrossRef]
6. Tulet, J.-C. Peru as a new major actor in Latin American coffee production. *Lat. Am. Perspect.* **2010**, *37*, 133–141. [CrossRef]
7. Salas López, R.; Gómez Fernández, D.; Silva López, J.O.; Rojas Briceño, N.B.; Oliva, M.; Terrones Murga, R.E.; Iliquín Trigoso, D.; Barboza Castillo, E.; Barrena Gurbillón, M.Á. Land suitability for coffee (*Coffea arabica*) growing in Amazonas, Peru: Integrated use of AHP, GIS and RS. *ISPRS Int. J. Geo-Inf.* **2020**, *9*, 673. [CrossRef]
8. Pham, Y.; Reardon-Smith, K.; Mushtaq, S.; Cockfield, G. The impact of climate change and variability on coffee production: A systematic review. *Clim. Chang.* **2019**, *156*, 609–630. [CrossRef]
9. Lechthaler, F.; Vinogradova, A. The climate challenge for agriculture and the value of climate services: Application to coffee-farming in Peru. *Eur. Econ. Rev.* **2017**, *94*, 45–70. [CrossRef]
10. Yllescas, J.; Vega, H.; De La Cruz, P.; Pantoja, J.; Cancho-Rodriguez, E. System Based on Market Segmentation to Improve the Export of Peruvian Coffee. *Eur. Bus. Manag.* **2022**, *8*, 55–61. [CrossRef]

11. Duran, R.F.A.; Sernaque, F.R.C.; Sirlopu, J.R.R.; Moncada, J.J.R. Forecasting the export competitiveness of Peruvian coffee in major importing countries usingautoregressive integrated moving average modeling. *Rev. Científica Pakamuros* **2024**, *12*, 126–137. [CrossRef]
12. Córdova, Y.M.P.; Villena, F.C.; Cabrera, M.A.L.; Juwau, J.M.; Rodríguez, V.H.P. Peru-Germany: Impact of COVID-19 on coffee agro-exports 2018–2021. *Sapienza Int. J. Interdiscip. Stud.* **2022**, *3*, 159–174. [CrossRef]
13. INACAL. *Guide for the Implementation of the Peruvian Technical Standard NTP 209.310:2019. PERGAMINO COFFEE. Requirements*; INACAL: Lima, Peru, 2021.
14. INACAL. *Guide for the Implementation of the Peruvian Technical Standard NTP 209.027:2018. COFFEE. Green Coffee. Requirements*; INACAL: Lima, Peru, 2021.
15. SCAA. *Protocols Cupping Speciality Coffee Speciality Coffee Association of America*; SCAA: Irvine, CA, USA, 2015; pp. 1–7.
16. Corrêa, P.C.; Oliveira, G.H.H.; Rodrigues, P.L.; Campos, S.C.; Botelho, F.M. Hygroscopic equilibrium and physical properties evaluation affected by parchment presence of coffee grain. *Span. J. Agric. Res.* **2010**, *8*, 694–702. [CrossRef]
17. Taveira, J.H.D.S.; Borém, F.M.; Da Rosa, S.D.V.F.; Oliveira, P.D.; Giomo, G.S.; Isquierdo, E.P.; Fortunato, V.A. Post-harvest effects on beverage quality and physiological performance of coffee beans. *Afr. J. Agric. Res.* **2015**, *10*, 1457–1466. [CrossRef]
18. Adriá, F.; Vorsitzender, E. *Coffee Sapiens: Innovation Through Understanding*; Phaidon: New York, NY, USA, 2019.
19. Vanesa, D.; Ana, P. Occurrence of Ochratoxin A in coffee beans, ground roasted coffee and soluble coffee and method validation. *Food Control* **2013**, *30*, 675–678. [CrossRef]
20. Esquivel, P.; Viñas, M.; Steingass, C.B.; Gruschwitz, M.; Guevara, E.; Carle, R.; Schweiggert, R.M.; Jiménez, V.M. Coffee (*Coffea arabica* L.) by-products as a source of carotenoids and phenolic compounds—Evaluation of varieties with different peel color. *Front. Sustain. Food Syst.* **2020**, *4*, 590597. [CrossRef]
21. Constantino, L.M.; Gil, Z.N.; Montoya, E.C.; Benavides, P. Coffee berry borer (*Hypothenemus hampei*) emergence from ground fruits across varying altitudes and climate cycles, and the effect on coffee tree infestation. *Neotrop. Entomol.* **2021**, *50*, 374–387. [CrossRef]
22. Whittaker, L.; González-Moreno, P.; Lowry, A.; Vélez, L.J.; Aristizábal, V.; Aristizábal, L.F.P.; Edgington, S.; Murphy, S.T. The effect of an altitudinal gradient on the abundance and phenology of the coffee berry borer (*Hypothenemus hampei*)(ferreri)(Coleoptera: Scolytidae) in the Colombia Andes. *Int. J. Pest Manag.* **2024**, 1–12. [CrossRef]
23. Silva, L.C.F.; Pereira, P.V.R.; da Cruz, M.A.D.; Costa, G.X.R.; Rocha, R.A.R.; Bertarini, P.L.L.; do Amaral, L.R.; Gomes, M.S.; Santos, L.D. Enhancing sensory quality of coffee: The impact of fermentation techniques on *Coffea arabica* cv. Catiguá MG2. *Foods* **2024**, *13*, 653. [CrossRef] [PubMed]
24. Bilen, C.; El Chami, D.; Mereu, V.; Trabucco, A.; Marras, S.; Spano, D. A systematic review on the impacts of climate change on coffee agrosystems. *Plants* **2022**, *12*, 102. [CrossRef]
25. Alvarado, C.W.; Bobadilla, L.G.; Valqui, L.; Valqui, G.S.; Valqui-Valqui, L.; Vigo, C.N.; Vásquez, H.V. Characterization of *Coffea arabica* L. parent plants and physicochemical properties of associated soils, Peru. *Heliyon* **2022**, *8*, e10895. [CrossRef]
26. Osorio Pérez, V.; Pabón Usaquén, J.P.; Calderón Tulcán, P.A.; Imbachí Quinchua, L.C. Physical and sensory quality and chemical composition of coffee grown in the Department of Huila. *Rev. Cenicafé* **2021**, *72*, e72201. [CrossRef]
27. Coayla, E.; Bedón, Y. Peruvian organic agro-exports, climate change and food security. *Rev. Econ. Sociol. Rural* **2024**, *62*, e282838. [CrossRef]
28. Montero-Mora, A.; Badia-Miró, M. Mild Arabica coffee trade at a time of market regulation. *Econ. Hist. Dev. Reg.* **2024**, *39*, 196–217. [CrossRef]
29. Ninaquispe, J.C.M.; María, A.P.S.; Vallejo, I.A.O. Commercial dynamics of Peruvian coffee exports to the European Union 2017-2021. *Alfa Rev. Investig. Cienc. Agronómicas Vet.* **2023**, *7*, 175–183.
30. Pancsira, J. International Coffee Trade: A literature review. *J. Agric. Inform.* **2022**, *13*, 26–35. [CrossRef]
31. Prilliadi, H.; Birinci, A. A Study on Determinants of Coffee Export from Indonesia to The United States of America. *J. Inst. Sci. Technol.* **2023**, *13*, 2174–2184. [CrossRef]
32. Merga Sakata, W.; Gebreselassie Abtew, W.; Garedew, W. Organoleptic quality attributes and their association with morphological traits in Arabica coffee (*Coffea arabica* L.) genotypes. *J. Food Qual.* **2022**, *2022*, 2906424. [CrossRef]
33. Coelho, E.G.; Bertarini, P.L.L.; Gomes, M.S.; Amaral, L.R.; Zotarelli, M.F.; Santos, L.D.; Santana, R.C. Physicochemical and Sensory properties of *Arabica* coffee beans of Arara cv. dried using different methods. *Foods* **2024**, *13*, 642. [CrossRef] [PubMed]
34. Simmer, M.M.B.; Soares da Silva, M.d.C.; Pereira, L.L.; Moreira, T.R.; Guarçoni, R.C.; Veloso, T.G.R.; da Silva, I.M.R.; Entringer, T.L.; Kasuya, M.C.M.; da Luz, J.M.R. Edaphoclimatic conditions and the soil and fruit microbiota influence on the chemical and sensory quality of the coffee beverage. *Eur. Food Res. Technol.* **2022**, *248*, 2941–2953. [CrossRef]
35. Getachew, M.; Tolassa, K.; De Frenne, P.; Verheyen, K.; Tack, A.J.M.; Hylander, K.; Ayalew, B.; Boeckx, P. The relationship between elevation, soil temperatures, soil chemical characteristics, and green coffee bean quality and biochemistry in southwest Ethiopia. *Agron. Sustain. Dev.* **2022**, *42*, 61. [CrossRef]

36. Salazar, J.C.S.; Rodríguez Burgos, E.; Duran-Bautista, E.H. Effect of culture conditions, the chemical characteristics of soil and grain handling in the sensory attributes of coffee (*Coffea arabica* L.) in cup. *Acta Agron.* **2015**, *64*, 342–348.
37. Mintesnot, A.; Dechassa, N.; Mohammed, A. Association of Arabica coffee quality attributes with selected soil chemical properties. *East Afr. J. Sci.* **2015**, *9*, 73–84.
38. Gamonal, L.E.; Vallejos-Torres, G.; López, L.A. Sensory analysis of four cultivars of coffee (*Coffea arabica* L.), grown at different altitudes in the San Martin region-Peru. *Ciência Rural* **2017**, *47*, e20160882. [CrossRef]
39. Velásquez, S.; Banchón, C.; Chilán, W.; Guerrero-Casado, J. Effect of three post-harvest methods at different altitudes on the organoleptic quality of C. canephora coffee. *Beverages* **2022**, *8*, 83. [CrossRef]
40. Silveira, A.d.S.; Pinheiro, A.C.T.; Ferreira, W.P.M.; Silva, L.J.d.; Rufino, J.L.d.S.; Sakiyama, N.S. Sensory analysis of specialty coffee from different environmental conditions in the region of Matas de Minas, Minas Gerais, Brazil. *Rev. Ceres* **2016**, *63*, 436–443. [CrossRef]
41. Hu, R.; Xu, F.; Chen, X.; Kuang, Q.; Xiao, X.; Dong, W. The Growing Altitude Influences the Flavor Precursors, Sensory Characteristics and Cupping Quality of the Pu'er Coffee Bean. *Foods* **2024**, *13*, 3842. [CrossRef] [PubMed]
42. da Silva Oliveira, E.C.; da Luz, J.M.R.; de Castro, M.G.; Filgueiras, P.R.; Guarçoni, R.C.; de Castro, E.V.R.; da Silva, M.d.C.S.; Pereira, L.L. Chemical and sensory discrimination of coffee: Impacts of the planting altitude and fermentation. *Eur. Food Res. Technol.* **2022**, *248*, 659–669. [CrossRef]
43. Wondimkun, Y.W.; Emire, S.A.; Esho, T.B. Investigation of physical and sensory properties of Ethiopian specialty dry processed green coffee beans. *Acta Univ. Cibiniensis. Ser. E Food Technol.* **2020**, *24*, 39–48. [CrossRef]
44. Gonzalez-Sanchez, B.; Sandoval-Gonzalez, O.; Flores-Cuautle, J.d.J.A.; Landeta-Escamilla, O.; Portillo-Rodriguez, O.; Aguila-Rodriguez, G. A Study of the Physical Characteristics and Defects of Green Coffee Beans That Influence the Sensory Notes Using Machine Learning Models. *Processes* **2023**, *12*, 18. [CrossRef]
45. Vega, A.; De León, J.A.; Reyes, S.M.; Gallardo, J.M. Mathematical model to determine the correlation between physicochemical parameters and the sensory quality of Panama Geisha and Pacamara coffee. *Inf. Tecnológica* **2021**, *32*, 89–100. [CrossRef]
46. Barbosa, M.d.S.G.; dos Santos Scholz, M.B.; Kitzberger, C.S.G.; de Toledo Benassi, M. Correlation between the composition of green Arabica coffee beans and the sensory quality of coffee brews. *Food Chem.* **2019**, *292*, 275–280. [CrossRef]
47. Worku, M.; De Meulenaer, B.; Duchateau, L.; Boeckx, P. Effect of altitude on biochemical composition and quality of green arabica coffee beans can be affected by shade and postharvest processing method. *Food Res. Int.* **2018**, *105*, 278–285. [CrossRef]
48. Tolessa, K.; D'Heer, J.; Duchateau, L.; Boeckx, P. Influence of growing altitude, shade and harvest period on quality and biochemical composition of Ethiopian specialty coffee. *J. Sci. Food Agric.* **2017**, *97*, 2849–2857. [CrossRef]
49. Sarmiento-Soler, A.; Rötter, R.P.; Hoffmann, M.P.; Jassogne, L.; van Asten, P.; Graefe, S.; Vaast, P. Disentangling effects of altitude and shade cover on coffee fruit dynamics and vegetative growth in smallholder coffee systems. *Agric. Ecosyst. Environ.* **2022**, *326*, 107786. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.