Research article

Effect of growing conditions and postharvest processing on arabica coffee bean physical quality features and defects

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HIGHLIGHTS

- Coffee bean physical features and defects were mainly affected by elevation.
- Production system also affected coffee bean physical features and defects.
- Production system effect on dry beans to red cherries ratio and bean physical features depended on postharvest processing.
- Shade effect on the proportion of large beans depended on the postharvest processing.

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ABSTRACT

The individual and interaction effects of elevation, production system (PS), shade and postharvest processing (PHP) on the ratio of dry beans to red cherries and the green bean physical quality features and defects of arabica coffee in southwestern Ethiopia were evaluated. The results showed that, with increasing elevation, the proportions of the total defected beans and large beans decreased while that of medium beans increased. Moreover, the proportion of secondary defects, 1000 seed weight and bean volume were higher for lowland and midland coffees than for highland coffee, but bean density was higher for highland than for lowland and midland coffees. The proportion of the total defected beans was also higher for modern plantation coffee in lowland than for modern plantation and semi-plantation coffees in midland and highland, but the 1000 seed weight was lower for semi-plantation coffee in highland than for modern plantation coffee in lowland and midland. The ratio of primary and secondary defects respectively was higher for dry- and wet-processed coffee in lowland than for dry- and wet-processed coffees in midland and highland. But, the ratio of small beans was lower for wet-processed coffee in lowland than for dry-processed coffee across elevations. The ratio of dry beans to red cherries and the 100 beans volume were higher for wet-processed modern plantation and semi-plantation coffees in midland than for dry-processed coffees of both production systems across elevations. However, the ratio of large beans was higher (1) for wet-processed modern plantation coffee in lowland than for dry- and wet-processed coffees of both production systems across elevations, and (2) for coffee that was grown without shade and wet-processed in lowland than for other coffees. Bean density was higher for dry-processed modern plantation and semi-plantation coffee in midland and highland, respectively than for other coffees across elevations. Overall, these results underlined the primary effects of elevation and PS, and the complex interaction effects between PHP and PS or shade on the ratio of dry beans to red cherries and the physical features and defects of green arabica coffee beans.

1. Introduction

The ratio of dry beans to red cherries, and bean physical features and defects are among the major criteria commonly used to evaluate yield and quality of green coffee beans, respectively. In Ethiopia, the ratio of dry beans to red cherries is one of the main variables used to estimate bean yield; and the evaluation of the bean physical quality covers 40% of the total preliminary quality assessment of green coffee beans (Worku et al., 2016). The presences of different bean physical features (e.g., color, weight, size, shape, density) and defective beans (e.g., discolored,

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immature, broken, insect-damaged, wrinkled, withered, shell/elephant, triage beans) during processing and roasting contribute to off-flavors and reduce the overall cup quality (Casas et al., 2017; Hameed et al., 2018a; Marie et al., 2020). Defective coffee beans are also lower in weight, density and brightness as well as contents of some quality precursor biochemicals (e.g., caffeine, protein, lipid, sucrose and total polyphenols) compared to normal (graded) beans (Ramalakshmi et al., 2007). This shows that defective beans reduce not only cup quality, but also biochemical and yield (quantity) parameters of coffee.

Multiple factors, such as genetics, plant physiology and age, growing environments, diseases and pests, management practices, and harvesting and postharvest processing practices influence the ratio of dry beans to red cherries, and the physical features and defects of coffee beans (Bote and Vos, 2017; Hameed et al., 2018a, 2018b; Läderach et al., 2011; Nugroho et al., 2016). A review by Hameed et al. (2018a) indicates the influence of variety, growing environment, geographical topography (especially elevation and slope) and agricultural practice on physical and biochemical coffee features. Coffee variety, growing environment (e.g., rainfall, frost, temperature, and sun and shade ecosystems), agronomic practices (e.g., soil fertilization) and harvesting strategy play a decisive role in shaping not only quality attributes of coffee but also the postharvest processing approaches of coffee. Several studies also reported the interaction effects between different growing environments (e.g., between elevation and shade) and between growing environment (e.g., elevation, shade) and genotype or agronomic practices (e.g., fruit thinning, N fertilization) on bean physical features, such as bean weight and size (Bote and Vos, 2017; Hameed et al., 2018a; Neto et al., 2018), between shade and harvest period on bean weight (Tolessa et al., 2017), and between shade and postharvest processing on bean physical quality scores (Worku et al., 2018).

In Ethiopia, coffee is produced under four different production systems, namely forest, semi-forest, garden and plantation coffees in a range of elevations (ca. 850–2300 m asl) and processed by dry and wet processing methods. These production systems vary in their features influencing the coffee quality, including physical features and defects of green coffee beans. For example, the coffee management level varies from little or none in the forest coffee to intensive in the plantation coffee, and a shade tree canopy cover from ca. $\leq$ 30% for garden and plantation coffees to ca. $\geq$ 85% for forest coffee (Gole, 2015). Improved varieties and agronomic practices, including agrochemicals and pruning, are usually used in plantation coffee, but rarely in other systems (Wiersum, 2010; Gole, 2015). A study by Geeraert et al. (2019) indicated that increasing the forest management intensity negatively affects coffee quality. And, the most important drivers of deteriorating coffee quality include decreased shade levels and changing micro-climate and biotic interactions. Rainfall and temperature, which are the major climatic variables influencing coffee bean development and quality, also vary with elevation in Ethiopia (Woube, 1999; Kassa, 2017). However, to the best of our knowledge, there are no studies that analyze the individual and interactive effects of growing elevation, coffee production system, shade and postharvest processing on the ratio of dry beans to fresh cherries and bean physical quality attributes and defects of coffee. Especially for Ethiopian coffee, this information is not available. Moreover, regardless of its variation due to the variety (genetics), growing environment, cultivation practice and postharvest processing, a single ratio of dry beans to red cherries (i.e., 1:6) is commonly used during yield and productivity estimation of Ethiopian coffee. Hence, the main objective of the present study was to examine the individual and interactive effects of these factors on the ratio of dry beans to red cherries and on green bean physical quality features and defects of arabica coffee in southwestern Ethiopia.

2. Materials and methods

2.1. Description of the study sites

Coffee samples were collected in the 2014-2015 and 2015-2016 cropping seasons from 19 specific sites or farms located at 4 locations (Choche, Gomma II, Limmu-Kossa and Gera) and a range of elevations (1470–2010 m asl) in three districts (Gomma, Limmu-Kossa and Gera), which are among the major coffee-growing districts in southwestern Ethiopia.

Southwestern Ethiopia is one of the major coffee-growing regions of Ethiopia. It is generally characterized by a hot and humid tropical rainforest climate with a unimodal rainfall and a long rainy period, from February to November. The mean annual total rainfall and temperature of the region ranges from ca. 1000 to 2400 mm and 13 to 27.8 °C (Woube, 1999; Kassa, 2017). The highlands of the region are dominated by nitosols, vertisols, leptosols, regosols, cambisols, alisols and acrisols (Dewitte et al., 2013) and the coffee-growing areas of the region by nitosols (Teketay, 1999). In the region, both dry-processed and wet-processed green arabica coffee beans are produced, and coffee is cultivated under four different production systems (forest, semi-forest, garden and plantation coffee); of which semi-forest coffee is the dominant one.

These production systems vary in their management level, vegetation structure, shade tree species diversity and canopy cover, and genetic diversity, population density and structure of coffee plants (Worku et al., 2015). The level of coffee management increases from little or none in forest coffee to intensive in plantation coffee and shade tree canopy cover from ca. $\leq$ 30% in garden and plantation coffees to ca. $\geq$ 85% in forest coffee (Gole, 2015). Clearing of plants competing with coffee, reducing the large canopy trees to open up the canopy, protecting and thinning of naturally regenerated coffee seedlings and planting of coffee in open areas are the main agronomic practices applied in semi-forest coffee. The shade tree canopy cover in this system is about 40–60% (Wiersum, 2010; Gole, 2015). Garden coffee is commonly present around homesteads and consists of few shade trees (30–60 trees ha^{-1}) with 30–40% canopy cover and other crops, such as *enset,* banana, fruit trees, root crops, vegetables, spices, maize, *chat,* etc. (Gole, 2015). Improved varieties and agronomic practices including seed preparation, nursery management, plant spacing, mulching, weeding, fertilizer and herbicide application and pruning are usually used in plantation coffee, but rarely in other systems (Wiersum, 2010; Gole, 2015).

Besides the four major production systems, a subsystem, like a semi-forest plantation coffee or a semi-plantation coffee also exists. In this system, there is a higher management intensity, including systematic coffee planting, planting of improved coffee varieties and slashing of weeds, and a lower shade tree species diversity and canopy cover compared to that in semi-forest coffee, but with a lower management intensity compared to that in garden and planation coffees (Worku et al., 2015).

The 19 specific sampling sites were: (1) Farm 2 (1470 m asl, Choche), (2) Hora (1470 m asl, Choche), (3) Sele (1508 m asl, Choche), (4) Farm 3 (1515 m asl, Choche), (5) Farm 1 (1516 m asl, Choche), (6) Gema Sefer (1523 m asl, Choche), (7) Great Chale (1559 and 1561 m asl, Choche), (8) Sobo (1569 m asl, Choche), (9) Subfarm 03-B1 (1660 m asl, Gomma II), (10) Subfarm 03-B4 (1660 m asl, Gomma II), (11) Subfarm 03-B6 (1740 m asl, Gomma II), (12) Subfarm 04-B1-4 (1740 m asl, Gomma II), (13) Subfarm 03-B3 (Gecho) (1760 m asl, Gomma II), (14) Subfarm 04-B3 (1820 m asl, Gomma II), (15) Subfarm 03 (Abamestet) (1885 m asl, Limmu-Kossa), (16) Subfarm 03-B1 (1906 m asl, Limmu-Kossa), (17) Subfarm 03-B6 (2000 m asl, Limmu-Kossa), (18) Sefera (2000 m asl, Gera), and (19) Genjichala (2004 and 2010 m asl, Gera). Gomma II, located at 7°57′N, 36°37′E and 1450–1750 m asl, receives 1540 mm mean annual total rainfall and has 13.0 and 29.0 °C mean annual minimum and maximum temperatures, respectively. Choche is located at about 10 km from Gomma II. Limmu-Kossa, located at 7°57′N, 36°53′E and 1600–2000 m asl, receives 1920 mm mean annual total rainfall and has 12.0 and 27.0 °C mean annual minimum and maximum temperatures, respectively (CPDE, 2011). Gera is located at 7°39′N, 36°14′E and 1500–2900 m asl and receives 1880 to 2080 mm mean annual total rainfall and has 10 and 26 °C mean annual minimum and maximum temperatures, respectively (Regassa, 2015; Degaga, 2017).

2.2. Research design and sample collection

Coffee samples (n = 38, each of 12 kg of fresh red cherries) were collected during two cropping seasons from the 19 specific sites or farms located at 4 locations (Choche = 8 sites, Gomma II = 5 sites, Limmu-Kossa = 3 sites and Gera = 3 sites) (see above) and 3 elevation ranges (lowland: < 1550 m asl, midland: 1550–1900 m asl and highland: > 1900 m asl). In each elevation range, two coffee production systems (modern plantation and semi-plantation) and 2 coffee shade levels (no shade: 0% and shade: 30–40% coffee shrubs' canopy overhead shade) were considered and the collected samples were processed by 2 post-harvest processing methods (dry and wet). The number of samples per elevation range was 12 for lowland (6 samples from modern plantation coffee and 6 samples from semi-plantation coffee), 16 for midland (10 samples from modern plantation coffee and 6 samples from semi-plantation coffee) and 10 for highland (4 samples from modern planta-tion coffee and 6 samples from semi-plantation coffee). The number of samples per shade level was 19. Each fresh cherry sample was divided into two equal-parts (6 kg each) and each part was processed by either the dry or the wet postharvest processing method to get dry coffee beans. More details of sample processing by using dry and wet processing methods are available in Worku et al. (2018). During sample collection, the 2 shade levels were considered for each of the 2 production systems at each location in each elevation range, but due to their unavailability at all locations, both production systems were not considered for each location and a specific site at each location. The locations and the sites within each location were purposively selected for sample collection primarily based on their elevation to include all three coffee-growing agro-ecological zones (lowland, midland and highland areas) and the availability of the two coffee production systems.

2.3. Data collection

Data on weights of fresh red cherries (12 kg per sample), dry beans at 11.5% moisture content, defected beans (beans with primary defects, beans with secondary defects and total defected beans), 1000 seed weight and beans with different sizes (large beans: ≥ 17 screen size, medium beans: 15 and 16 screen sizes, small beans: 14 screen size and shells beans: < 14 screen size) as well as volumes of 100 g beans and individual beans were taken. Worku et al. (2016) has more details on primary and secondary defects. Next, based on these data, different ratios [dry beans:red cherries ratio, primary defects:total beans ratio, secondary defects:total beans ratio, total defects (primary defects + secondary defects):total beans ratio, large beans:total beans ratio, medium bean-s:total beans ratio, small beans:total beans ratio, shell beans:total beans ratio], bean density and average individual bean volume were calculated.

2.4. Statistical methods

The effects of (1) elevation range (3 levels: lowland, midland and highland), (2) production system (2 levels: modern-plantation and semi-plantation), (3) shade (2 levels: no shade and shade), (4) postharvest processing (2 levels: dry and wet), and (5) two- and three-way in-teractions between production system, shade and postharvest processing on the dry beans:red cherries ratio, the primary defects:total beans ratio, the secondary defects:total beans ratio, the total defects:total beans ratio, the large beans:total beans ratio, the medium beans:total beans ratio, the small beans:total beans ratio, the shell beans:total beans ratio, 1000 seed weight, 100 g bean volume, average individual bean volume and bean density were examined using a Nested-Crossed design. A factor is nested in another factor when the levels used in the other factor are similar but not identical, and a factor is crossed with another factor when the levels used in the other factor are identical (Montgomery, 2020). Production system, shade and postharvest processing are crossed, and they are nes-ted within the elevation range. The components of the model are shown in the Source of Variation column (first column) of Tables 1 and 2. The analysis was conducted using the Mixed procedure of SAS 9.4 (SAS, 2014). For each response variable, the validity of model assumptions was verified by examining the residuals as described in Montgomery (2020). For significant (p < 0.05) effects, multiple means comparison was con-ducted using the least squares means statement of Proc Mixed at the 1% level of significance.

3. Results

The ANOVA p-values showing the significance of the main effect of elevation range (ER), and the main and interaction effects of production system (PS), shade (Sh) and postharvest processing (PHP), all nested in ER, on the ratio of dry beans:red cherries and the physical quality defects and features of green arabica coffee beans are shown in Tables 1 and 2. Accordingly, the studied factors (ER, PS, Sh and PHP) have different ef-fects on the 12 response variables.

Elevation significantly affected all response variables, except the dry beans:red cherries ratio (DB:RC), small beans:total beans ratio (SB:TB) and shell beans:total beans ratio (ShB:TB). PS, nested in ER, significantly affected the primary defects:total beans ratio (PD:TB), secondary defects:total beans ratio (SD:TB), total defects:total beans ratio (TD:TB) and 1000 seed weight (1000SW). PHP, nested in ER, significantly affected the PD:TB, SD:TB and SB:TB. PS*PHP interaction effect, nested in ER, significantly affected the DB:RC, large beans:total beans ratio (LB:TB), 100 g bean volume (100BV) and bean density (BD). Sh*PHP interaction effect, nested in ER, on the LB:TB was also significant. However, shade, and PS*Sh and PS*Sh*PHP interactions, all nested in

Table 1. ANOVA p-values showing the significance of the main effect of elevation range (ER), and the seven main and interaction effects of production system (PS), shade (Sh) and postharvest processing (PHP), all nested in ER, on the dry beans:red cherries ratio and proportions of green beans with different physical defects and screen sizes.

Source of variation	DB:RC	PD:TB	SD:TB	TD:TB	LB:TB	MB:TB	SB:TB	ShB:TB
ER	0.109	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	0.076	0.415
PS(ER)	0.042	**0.009**	**0.046**	**0.027**	0.384	0.161	0.148	0.091
Sh(ER)	0.824	0.319	0.423	0.365	0.930	0.699	0.248	0.565
PHP(ER)	0.001	**0.001**	**0.003**	0.288	0.021	0.405	**0.007**	0.223
PS*Sh(ER)	0.579	0.536	0.657	0.773	0.939	0.807	0.963	0.628
PS*PHP(ER)	**0.017**	0.678	0.816	0.740	**0.023**	0.080	0.219	0.351
Sh*PHP(ER)	0.322	0.135	0.588	0.347	**0.011**	0.066	0.131	0.314
PS*Sh*PHP(ER)	0.561	0.493	0.573	0.492	0.609	0.285	0.830	0.970
$\sqrt{MSE}$	0.012	0.037	0.037	0.100	0.086	0.063	0.043	0.014

DB:RC = Dry beans:red cherries ratio, PD:TB = primary defects:total beans ratio, secondary SD:TB = defects:total beans ratio, TD:TB = total defects:total beans ratio, LB:TB = large beans:total beans ratio, MB:TB = medium beans:total beans ratio, SB:TB = small beans:total beans ratio, ShB:TB = shell beans:total beans ratio. $\sqrt{MSE}$ = the square root of the Mean Squares Error (*MSE*), which estimates the common standard deviation (σ).
Significant effects that require comparison of multiple means are shown in bold.

Table 2. ANOVA p-values showing the significance of the main effect of elevation range (ER), and the seven main and interaction effects of production system (PS), shade (Sh) and postharvest processing (PHP), all nested in ER, on the weight, volume and density of green beans.

Source of variation	1000SW	100BV	AIBV	BD
ER	**0.001**	**0.002**	**0.001**	**0.002**
PS(ER)	**0.046**	0.001	0.089	0.001
Sh(ER)	0.904	0.285	0.887	0.284
PHP(ER)	0.387	0.001	0.159	0.001
PS*Sh(ER)	0.643	0.192	0.819	0.194
PS*PHP(ER)	0.985	**0.001**	0.689	**0.001**
Sh*PHP(ER)	0.706	0.483	0.812	0.491
PS*Sh*PHP(ER)	0.957	0.968	0.949	0.968
$\sqrt{MSE}$	9.954	0.851	0.009	0.011

1000SW = 1000 seed weight, 100BV = 100 g bean volume, AIBV = average individual bean volume, BD = bean density. $\sqrt{MSE}$ = the square root of the Mean Squares Error (*MSE*), which estimates the common standard deviation (σ). Significant effects that require comparison of multiple means are shown in bold.

ER, affected none of the studied variables. Moreover, ShB:TB was not significantly affected by any of the studied factors (Tables 1 and 2).

3.1. Elevation effect

Elevation significantly (p < 0.05) affected all considered response variables, except the dry beans:red cherries ratio, small beans:total beans ratio and shell beans:total beans ratio (Tables 1 and 2). As indicated in Table 3, the primary defects:total beans ratio was higher for lowland coffee than for midland and highland coffees and the secondary defects:total beans ratio for lowland and midland coffees than for highland coffee. However, the total defects:total beans ratio and large beans:total beans ratio decreased across lowland to highland while the medium beans:total beans ratio decreased across highland to lowland. The 1000 seed weight was higher for lowland coffee than for highland coffee. Bean volume was higher for lowland and midland coffees than for highland coffee, but bean density was higher for highland coffee than for lowland and midland coffees. In general, lowland coffee was higher in proportions of defected beans and large beans, bean weight and bean volume, whereas highland coffee was higher in proportions of medium beans and bean density. The results of the large beans:total beans ratio and medium beans:total beans ratio, and bean volume and bean density showed an inverse trend across the three elevation ranges while that of the proportion of secondary defects and bean volume, and the proportion of total defects and large beans showed a similar trend (Table 3). However, there was no significant difference between lowland and midland coffees in secondary defects, bean weight, bean volume and bean density, and between midland and highland coffees in primary defects and bean weight (Table 3).

3.2. Production system effect

The coffee production system, nested in ER, significantly (p < 0.05) affected the primary defects:total beans ratio, the secondary defects:total

beans ratio, the total defects:total beans ratio and the 1000 seed weight (1000SW) (Tables 1 and 2). The results of the main effect of coffee production system on proportions of defected beans, 1000 seed weight and individual bean volume within each of the three elevation ranges (lowland, midland and highland) are shown in Table 4. The primary defects:total beans ratio of modern plantation coffee in lowland was significantly higher than that of semi-plantation coffees across the elevation range and modern plantation coffee in midland and highland. The primary defects:total beans ratio of semi-plantation coffee in lowland was also higher than that in highland. The secondary defects:total beans ratio of modern plantation coffee in lowland was significantly higher than that of modern plantation coffees in midland and highland and semi-plantation coffee in highland. The secondary defects:total beans ratio of semi-plantation coffee in highland was lower than that of both production systems across the elevation range. Similarly, the total defects:total beans ratio of modern plantation coffee in lowland was significantly greater than that of both modern plantation and semi-plantation coffees in midland and highland, but that of semi-plantation coffee in highland was lower than that of both production systems in lowland and midland. The 1000 seed weight of semi-plantation coffee in highland was significantly lower than that of semi-plantation coffee in lowland and modern plantation coffees in lowland and midland (Table 4).

Overall, modern plantation coffee in lowland consisted of a higher proportion of defected beans (a lower proportion of pure beans) than both production systems in midland and highland while semi-plantation coffee in highland consisted of a lower proportion of defected beans and lighter beans than others (Table 4).

3.3. Shade effect

Shade and its interactions with the coffee production system and postharvest processing, nested in ER, affected none of the studied variables (p > 0.05), except for proportions of large beans that have been significantly (p < 0.05) affected by the interaction effect between shade and postharvest processing (Tables 1 and 2). The results of this interaction effect are presented in subsection 3.6.

Table 4. Mean values of the proportions of green beans with different defects and 1000 seed weight obtained from modern plantation (Modern) and semi-plantation (Semi) production systems (PS), nested within each of the three elevation ranges (ER): lowland, midland and highland.

PS(ER)	PD:TB	SD:TB	TD:TB	1000SW (g)
Modern (Lowland)	0.147 a	0.260 a	0.406 a	153.6 a
Modern (Midland)	0.073 bc	0.180 b	0.253 b	148.5 a
Modern (Highland)	0.067 bc	0.169 b	0.236 bc	144.8 ab
Semi (Lowland)	0.096 b	0.236 ab	0.333 ab	151.3 a
Semi (Midland)	0.082 bc	0.205 ab	0.288 b	144.1 ab
Semi (Highland)	0.050 c	0.076 c	0.126 c	133.5 b

PD:TB = Primary defects:total beans ratio, SD:TB = secondary defects:total beans ratio, TD:TB total defects:total beans ratio, 1000SW = 1000 seed weight. Within each column, means sharing the same letter are not significantly different.

Table 3. Mean values of the proportions of green beans with different defects and sizes, and the weight, volume and density of green beans obtained from the three elevation ranges (ER): lowland, midland and highland.

ER	PD:TB	SD:TB	TD:TB	LB:TB	MB:TB	1000SW(g)	100BV(mL)	AIBV (mL)	BD (gmL^{-1})
Lowland	0.121 a	0.248 a	0.370 a	0.264 a	0.585 c	152.5 a	88.2 a	0.135 a	1.13 b
Midland	0.078 b	0.193 a	0.270 b	0.190 b	0.634 b	146.3 ab	88.3 a	0.129 a	1.13 b
Highland	0.059 b	0.122 b	0.181 c	0.103 c	0.718 a	139.2 b	87.4 b	0.121 b	1.15 a

PD:TB = Primary defects:total beans ratio, SD:TB = secondary defects:total beans ratio, TD:TB total defects:total beans ratio, LB:TB = large beans:total beans ratio, MB:TB = medium beans:total beans ratio, 1000SW = 1000 seed weight, 100BV = 100 g bean volume, AIBV = average individual bean volume, BD = bean density. Within each column, means sharing the same letter are not significantly different.

3.4. Postharvest processing effect

Postharvest processing, nested in ER, significantly (p < 0.05) affected the primary defects:total beans ratio, the secondary defects:total beans ratio and the small beans:total beans ratio (Tables 1 and 2). Means based on the main effect of postharvest processing, nested in ER, on these variables are shown in Table 5. The primary defects:total beans ratio of dry-processed coffee continuously decreased across lowland to highland, but that of dry-processed coffees in midland and highland were not statistically different from that of wet-processed coffees in the three elevation ranges. In this attribute, there was also no significant difference among the wet-processed coffees at the three elevation ranges. The secondary defects:total beans ratio of wet-processed coffee in lowland was significantly higher than that of wet-processed coffees in midland and highland and dry-processed coffees in the three elevation ranges. Conversely, the secondary defects:total beans ratio of dry-processed coffee in highland was lower than that of dry-processed coffee in lowland plus wet-processed coffees in lowland and midland. The small beans:total beans ratio of wet-processed coffee in lowland was considerably lower than that of dry-processed coffees in all three elevation ranges, but that of wet-processed coffees in midland and highland and dry-processed coffees in all elevation ranges was not statistically different. This attribute was also similar for wet-processed coffees in the three elevation ranges (Table 5).

3.5. Interaction effect of production system and postharvest processing

The interaction effect between production system and postharvest processing, nested in ER, significantly (p < 0.05) affected the dry beans:red cherries ratio, large beans:total beans ratio, 100 g bean volume and bean density (Tables 1 and 2). As presented in Table 6, the dry beans:red cherries ratio of wet-processed modern plantation and semi-plantation coffees in midland was much more than that of wet-processed modern plantation coffee in highland and dry-processed coffees of both production systems across the three elevation ranges, excluding modern plantation coffee in highland. The dry beans:red cherries ratio of dry-processed semi-plantation coffee in midland was lower than that of all other coffees, except for dry-processed semi-plantation coffee in lowland and dry- and wet-processed modern plantation coffees in lowland and highland, respectively (Table 6).

The large beans:total beans ratio of wet-processed modern plantation coffee in lowland was higher than that of all other coffees across elevations. The large beans:total beans ratio of dry-processed modern plantation coffee in highland was considerably lower than that of wet-processed modern plantation coffees in lowland and midland, and dry- and wet-processed semi-plantation coffees in lowland (Table 6).

The 100 g bean volume of wet-processed modern plantation and semi-plantation coffees in midland was significantly higher than that of dry-processed coffees of both production systems across the three

Table 5. Mean values of the proportions of primary defects, secondary defects and small beans of coffee obtained from dry and wet postharvest processing (PHP), nested within each of the three elevation ranges (ER): lowland, midland and highland.

PHP(ER)	PD:TB	SD:TB	SB:TB
Dry (Lowland)	0.150 a	0.199 b	0.153 a
Dry (Midland)	0.095 b	0.168 bc	0.168 a
Dry (Highland)	0.052 c	0.091 c	0.168 a
Wet (Lowland)	0.093 bc	0.297 a	0.106 b
Wet (Midland)	0.061 bc	0.217 b	0.132 ab
Wet (Highland)	0.065 bc	0.154 bc	0.150 ab

PD:TB = primary defects:total beans ratio, SD:TB = secondary defects:total beans ratio, SB:TB = small beans:total beans ratio. Within each column, means sharing the same letter are not significantly different.

Table 6. Mean values of proportion of dry beans to red cherries, proportion of large beans and volume and density of green beans obtained from the combinations of production system (PS) and postharvest processing (PHP), each nested within each of the three elevation ranges (ER): lowland, midland and highland.

PS(ER)	PHP(ER)	DB:RC	LB:TB	100BV (mL)	BD (g mL^{-1})
M(Low)	Dry(Low)	0.103 cde	0.197 bcde	86.8 c	1.15 b
M(Low)	Wet(Low)	0.115 abc	0.386 a	88.7 ab	1.13 cde
M(Mid)	Dry(Mid)	0.111 c	0.148 bcde	85.2 d	1.17 a
M(Mid)	Wet(Mid)	0.126 a	0.244 bc	89.8 a	1.11 e
M(High)	Dry(High)	0.113 abcd	0.073 e	85.5 cd	1.17 ab
M(High)	Wet(High)	0.103 cde	0.104 cde	89.5 ab	1.12 cde
S(Low)	Dry(Low)	0.093 de	0.249 b	88.5 b	1.13 cd
S(Low)	Wet(Low)	0.114 abc	0.224 bcd	88.7 ab	1.13 cde
S(Mid)	Dry(Mid)	0.088 e	0.167 bcde	88.2 b	1.13 c
S(Mid)	Wet(Mid)	0.127 a	0.199 bcde	89.8 a	1.11 e
S(High)	Dry(High)	0.110 cd	0.091 de	85.3 d	1.17 a
S(High)	Wet(High)	0.117 abc	0.142 bcde	89.2 ab	1.12 cde

DB:RC = dry beans:red cherries ratio, LB:TB = large beans:total beans ratio, 100BV = 100 g bean volume, BD = bean density, M = modern plantation PS, S = Semi-plantation PS, Low = lowland, Mid = Midland, High = highland. Within each column, means sharing the same letter are not significantly different.

elevation ranges. Nevertheless, the 100 g bean volume of wet-processed coffee was similar for both production systems across the elevation (Table 6). Bean density showed a similar, but an opposite, trend with bean volume across production system and elevation. While wet-processed modern plantation and semi-plantation coffees in midland showed a lower bean density than that of all dry-processed coffees across production systems and elevations, dry-processed modern plantation coffee in midland and semi-plantation coffee in highland showed a higher bean density than that of all others, except dry-processed modern plantation coffee in highland (Table 6).

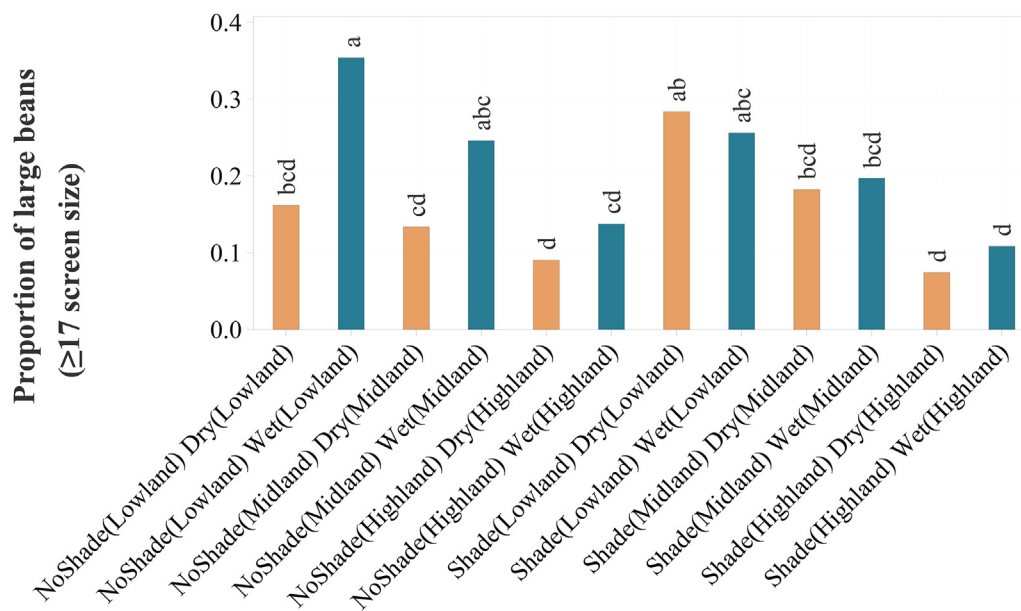### 3.6. Interaction effect of shade and postharvest processing

The interaction effect of shade and postharvest processing was significant (p < 0.05) only for the large beans:total beans ratio and its result is presented in Figure 1. The large beans:total beans ratio of without shade-grown and wet-processed coffee in lowland was significantly higher than that of all other coffees other than without shade-grown and wet-processed coffee in midland and shade-grown and dry- and wet-processed coffees in lowland. The large beans:total beans ratio of without shade-grown and wet-processed coffee in midland and shade-grown and dry- and wet-processed coffees in lowland was considerably higher than that of without shade-grown and dry-processed and shade-grown and dry- and wet-processed coffees in highland. However, that of without shade-grown and dry-processed coffees in all three elevation ranges, without shade-grown and wet-processed coffee in highland, and shade-grown and dry- and wet-processed coffees in midland and highland was not statistically different (Figure 1).

3.7. Interaction effect of production system, shade and postharvest processing

The three-way interaction between production system, shade and postharvest processing, nested in ER, affected none of the studied variables. The two-way interaction effect between production system and shade, nested in ER, also showed a similar result (Tables 1 and 2).

4. Discussion

Several studies have reported the influence of growing environment (e.g., elevation, shade) (Vaast et al., 2006; Somporn et al., 2012; Tolessa et al., 2017; Worku et al., 2018) and postharvest processing (Tolessa,

Shade (ER) Postharvest processing (ER)

Figure 1. Bar graph of the large beans:total beans ratio showing the interaction effect of shade and postharvest processing, each nested within each of the three elevation ranges (ER): lowland, midland and highland. Means sharing the same letter are not significantly different.

2017; Worku et al., 2018) on coffee beans. This study, however, expanded the scope and clarified individual and interaction effects of elevation, coffee production system, shade and postharvest processing on the ratio of dry beans to red cherries, and bean physical quality features and defects. The ratio of dry beans to red cherries is one of the key components used to estimate coffee bean yield. Physical defects and features of green beans have a direct impact on beverage quality. So, they are considered in coffee quality evaluation (Worku et al., 2016) that determines the market price of coffee. Through analysis of these features of green beans of arabica coffee samples collected from adult coffee shrubs grown with and without shade under modern plantation and semi-plantation coffee production systems and processed by a dry or wet method in lowland, midland and highland, the study showed the importance of elevation, production system and postharvest processing, and how these factors interact when affecting proportions of defective beans and beans with different sizes, and weight, volume and density. The results generally show that the effect of elevation on physical quality features and defects of green coffee beans is dominant over that of the other studied quality determinants. Moreover, the values of the ratio of dry beans to red cherries, which varied from 0.088 to 0.127 with a mean value of 0.110 (Table 6), are lower than the value that is currently used in coffee yield and productivity estimation in Ethiopia (i.e., ≈0.167). This indicates that the coffee yield in Ethiopia can be overestimated on average by 5.7%.

The dominant effect of elevation on physical quality features and defects of green coffee beans observed in this study agrees with that reported in previous studies (Tolessa et al., 2017; Worku et al., 2018) showing a dominant elevation effect on coffee quality and biochemical composition over that of shade, harvest period and postharvest processing. With increasing elevation, the proportions of defective beans and large beans decreased, but the proportions of medium beans and the density of beans increased. More than 80 and 70% of the beans in highland were clean and of medium size, respectively (Table 3). This shows that highland coffee scores better in bean physical quality and uniformity than lowland and midland coffees. Similarly, in previous studies (Tolessa et al., 2017; Worku et al., 2018), the proportions of higher quality grade (Grades 1 and 2) coffees increased with elevation.

These results support our previous knowledge on the presence of a strong relationship between elevation and quality of arabica coffee and between bean physical features and quality grade of coffee. It is, however, hard to explain why the effect of elevation on coffee quality dominates over that of other quality determinants, such as shade and postharvest processing.

Being highly affected by elevation, the relationship between elevation and coffee quality can mainly be linked to the temperature of the growing area (Muschler, 2001) and partly to other factors such as soil moisture (Carr, 2001; Moat et al., 2017) and coffee diseases and pests (Worku, 2019). Lower temperatures have been suggested to extend the maturation period of coffee berries that in turn leads to a better bean filling (Vaast et al., 2006; Lara-Estrada and Vaast, 2007). In addition, the negative effects of drought (Moat et al., 2017) and some coffee diseases and pests in Ethiopia (e.g., coffee leaf rust, coffee berry borer and Antestia bug) on coffee decrease with elevation (Daba et al., 2019; Garbaba and Garedew, 2019; Garedew et al., 2019). Consequently, coffee berries grown at higher elevations mature slowly with less growth constraints (e.g., moisture deficit, disease- and pest-induced stresses) and supply more assimilates to developing beans that allows a better bean development, which can lead to denser and purer beans than those grown at lower elevations. Parallel to this, as a quality evaluation of coffee includes green bean physical features and defects, the fraction of defective beans directly affects the quality grade of coffee and bean size distribution and density indirectly via their effect on proper roasting.

The significant elevation effect on 1000 beans weight in this study also agrees with that in Tolessa et al. (2017), who reported a significant variation between coffees grown in midland (1600–1680 m asl) and highland (1950–2100 m asl) in 100 beans weight and between open and dense shades (0 and 65–85%) in 100 beans weight and bean physical quality scores. In this study, however, coffee beans grown in midland and highland did not significantly differ in 1000 beans weight, being much higher for coffee grown in lowland than in highland (Tables 3). Moreover, all variables including 1000 beans weight and the fractions of beans with physical quality defects in this study did not vary due to the shade factor that consisted of two shade levels (0 and 30–40%). Similarly, Tolessa et al. (2017) observed no variation between 0 and 40–55% shade levels in 100 beans weight and physical and cup quality scores. The

significant variation between coffees grown in midland and highland in bean physical quality (Table 3) also contradicts with the results of Tolessa et al. (2017) that showed similar bean physical quality scores for coffees grown in midland and highland. On the other hand, the absence of elevation and shade interaction effect on weight and physical quality of green beans in the present study also concurs in previous studies (Tolessa et al., 2017; Worku et al., 2018). However, this study and the study by Worku et al. (2018) reported a shade and postharvest processing interaction effect on fractions of large and medium beans (Figure 1) and bean physical quality scores, respectively. Tolessa et al. (2017) also reported an elevation or a shade and harvest period interaction effect on bean physical quality scores and 100 beans weight, respectively.

Absence of shade effect on some quality features (e.g., size, weight, volume and density) of beans in this study and some attributes of cup quality (e.g., acidity, body, aroma, flavor and cup cleanness) in previous studies (Tolessa et al., 2017; Worku et al., 2018) as well as lighter beans for coffees grown in highland compared to that in lowland and midland (Table 3) are not in line with our expectation. In general, a higher elevation or shade causes a decrease in ambient temperature and infestation of some diseases and pests. This reduces heat-, disease- and pest-induced stresses in plants, increases leaf to fruit ratio and net photosynthetic rate, and prolongs the berry maturation period (DaMatta and Ramalho, 2006; Obso, 2006; Vaast et al., 2006). Under this situation, there is more supply of assimilates to developing beans and a longer period for bean filling. Shade has also been reported to reduce floral initiation and to allow more assimilate partitioning to each developing bean (Bosselmann et al., 2009). In this regard, the weight and density of coffee beans are expected to increase with elevation or shade as coffee berries grown at higher elevations or under shade mature slowly and their number per plant can be low (Vaast et al., 2006; Bosselmann et al., 2009), which allows a better bean filling.

On the other hand, a higher volume of beans with a lower density for the coffees grown in lowland and midland than for those grown in highland (Table 3) may indicate the positive influence of lower elevations (higher temperatures) on bean size or volume. However, bean size or volume is mainly determined by genetics (particularly that of the ovule or mother plant) and soil moisture during bean development (Wrigley, 1988). This is because the final size or volume of each bean is determined by elasticity of the parchment (an outer layer of an ovule) and the volume of the integument in each ovule before the parchment is lignified, creating an embryonic sac that is later on filled with endosperm. The integument volume is determined by soil moisture during the expansion phase of the berry development. It is, yet, difficult to conclude on this reasoning for our results due to lack of coffee genetics and soil moisture data of each sampling site and elevation range considered in the study.

Regarding coffee production system or postharvest processing vs. physical quality features and defects of green coffee beans, it is generally expected that modern plantation coffee or wet processing produces heavier beans with fewer defects compared to semi-plantation coffee or dry processing. This is because of the better management of coffee and removal of lighter and defective beans in the former than in the latter production system and processing method, respectively. Unlike this expectation, the present study shows a lower amount of defective beans for semi-plantation or dry-processed coffee in highland than for both production systems or processing methods in lowland and midland (Tables 4 and 5). The beans of semi-plantation coffee in highland were also lighter in their weight than that of both production systems in lowland and midland (Table 4). However, bean density for modern plantation coffee in midland and highland and for semi-plantation coffee in highland and processed by the dry method was higher than that of others (Table 6). In terms of elevation and production system, this is in line with our expectations.

A link between postharvest processing and coffee production system or shade in a range of elevations for the ratio of dry beans to red cherries, volume and density of beans (Table 6), and amounts of large beans (Figure 1; Table 6) clearly showed the presence of interaction between postharvest processing and coffee management or growing environment for the ratio of dry beans to red cherries and physical features of green arabica coffee beans. It also indicates the dependency of the ratio of dry beans to red cherries on growing and postharvest processing conditions of coffee. So, considering this situation can be helpful during estimation of coffee yield and productivity to reduce the gap between the estimated and actual data. To our knowledge, other than the study by Worku et al. (2018) showing an interaction effect of shade and postharvest processing on bean physical quality scores, this is the first report in that sense. Analogously, our findings showed higher ratios of dry beans to red cherries and large beans to the total amount of beans for wet processing of modern plantation and semi-plantation coffees in midland and modern plantation coffee in lowland, respectively than for dry processing of coffees of both production systems across elevations (Table 6). A higher amount of large beans was also observed for wet processing of without shade-grown coffees in lowland and midland than for dry processing of without shade-grown coffees across elevations and dry and wet processing of shade-grown coffees in midland and highland (Figure 1).

Yet, due to limited scientific evidence as to how the postharvest processing method influences the ratio of dry beans to red cherries and the physical quality features and defects of green coffee beans grown under different management intensities and in different environments (e.g., elevation and shade conditions), it is difficult to explain the actual reasons for these results. So, it needs further study. However, our results certainly reinforced the assumption of a previous study (Worku et al., 2018), which stated that the influence of elevation on quality attributes and biochemical compositions of green coffee beans could be affected by shade and postharvest processing. As indicated in the previous study, the influences of coffee production system, shade and postharvest processing on the ratio of dry beans to red cherries and the physical quality features and defects of green coffee beans grown in a range of elevations could also be site (e.g., growing climate, soil, or season) specific.

5. Conclusion

The results of our study indicate that the physical features (i.e., size, weight, volume and density) and defects of the green arabica coffee beans in southwestern Ethiopia during the study period were primarily influenced by elevation followed by coffee production system. The results also indicated an appreciable influence of postharvest processing, but a negligible effect of shade on these bean attributes. Besides, it showed that the ratio of dry beans to red cherries and the physical features and defects of coffee beans can be influenced by the main and interaction effects of multiple factors, such as elevation, production system and postharvest processing.

Specifically, higher amounts of medium size and clean green beans with higher density can be produced in highland than in lowland and midland. More clean beans can also be produced by using a semi-plantation production system in highland than using both systems in lowland and midland. Moreover, the bean physical quality of highland coffee can further be improved by using a dry processing method. It is likely to produce a higher ratio of dry beans:red cherries by using wet processing of modern plantation and semi-plantation coffees in midland than using dry processing across elevation. Dry processing of without shade- and shade-grown coffees in highland can produce a higher amount of medium size beans than dry and wet processing of without shade- and shade-grown coffees in lowland. Conversely, wet processing of without shade-grown coffees in lowland and midland and dry and wet processing of shade-grown coffees in lowland can produce a higher amount of large beans than dry processing of without shade-grown and dry and wet processing of shade-grown coffees in highland.

There was an inverse trend between (1) the amounts of large and medium size beans across postharvest processing, production system and elevation, (2) bean volume and density across postharvest processing, production system and elevation, and (3) the amounts of large and medium size beans across postharvest processing, shade and elevation.

Declarations

Data availability statement

The authors do not have permission to share data.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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