Effects of brew strength, brew yield, and roast on the sensory quality of drip brewed coffee

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Abstract: Drip brewed coffee is traditionally quantified in terms of its strength, also known as total dissolved solids (TDS), and its brewing yield, also known as percent extraction (PE). Early work in the 1950s yielded classifications of certain regimes of TDS and PE as "underdeveloped," "bitter," or "ideal," with the modifiers "weak" or "strong" simply correlated with TDS. Although this standard is still widely used today, it omits a rich variety of sensory attributes perceptible in coffee. In this work, we used response surface methodology to evaluate the influence of TDS and PE on the sensory profile of drip brewed coffee. A representative wet-washed *Arabica* coffee was roasted to three different levels (light, medium, or dark), with each roast then brewed to nine target brews that varied systematically by TDS and PE. Descriptive analysis found that 21 of the 30 evaluated attributes differed significantly across the brews for one or more experimental factors, yielding linear or second-order response surfaces versus TDS and PE. Seven attributes exhibited a significant response surface for all three roast levels tested: *burnt wood/ash flavor*, *citrus flavor*, *sourness*, *bitterness*, *sweetness*, *thickness*, and *flavor persistence*. An additional seven attributes also showed a significant response surface fit across some but not all roasts. Importantly, *sweetness* exhibited an inverse correlation with TDS irrespective of roast, while *dark chocolate flavor* and *blueberry flavor* decreased with TDS for medium roast. These results provide new insight on how to optimize brewing conditions to achieve desired sensory profiles in drip brewed coffee.

Keywords: coffee brewing, descriptive analysis, drip coffee, extraction, flavor profile, response surface methodology

Practical Application: This research provides guidance on how best to achieve specific flavor profiles in drip brewed coffee.

1. INTRODUCTION

The brewing of coffee is described by the relationship between two key brewing indices, the strength of the beverage and the brewing yield of soluble material extracted from the bed of dry coffee grounds. Strength is normally quantified with the total dissolved solids (TDS) expressed as mass percent, and brewing yield, often referred to as percent extraction (PE), is the mass of soluble material removed from the coffee grounds per initial dry mass of grounds (Lockhart, 1957). Mass conservation arguments (Ristenpart & Kuhl, 2017) demonstrate that the PE and TDS are linearly correlated, with the slope related to the "brew ratio," defined as the mass of applied water to mass of dry coffee. This fundamental relationship is taught to coffee brewing professionals worldwide (Lingle, 2011) and is visually represented by the Brewing Control Chart, which was originally published and distributed by the Coffee Brewing Institute in the 1950s (Lockhart, 1959; cf. Figure 1). The Brewing Control Chart allows for TDS and PE to be used as quality indices, and thus for quality to be compared among coffee brews. As shown in Figure 1, the nine overlaid zones on the Brewing Control Chart each express a different brewing quality; for example, a brew with low PE and high TDS is designated as a "*strong under developed*" coffee, while a brew of high PE and low TDS is *"weak bitter."* The center zone is identified as "ideal" for all brewed coffee. These overlaid quality zones are widely used in the coffee industry as guidelines to help brew coffee with greater consistency and quality.

Despite its widespread use, however, the Coffee Brewing Control Chart has practical limitations for modern brewing. The overlaid verbiage implies a "one size fits all" brewing approach with an *"ideal"* zone between 18% to 22% PE and 1.15% to 1.35% TDS. Additionally, the conflation of consumer preferences with sensory descriptions is potentially misleading (e.g., consumers might prefer coffee of varying bitterness intensity). Likewise, it is unclear whether "*developed/underdeveloped*" and *"strong/weak"* were intended to describe the taste of the brewed coffee or a quality designation of the specific numerical brewing indices. The division of the chart into nine rectangular zones also implies that small changes in PE or TDS (such as from 17.9% to 18.1%) yield abrupt changes in sensory quality, when in reality the changes in sensory quality should be a continuum.

Perhaps most importantly, the terms describing the various zones do not encompass the multitude of flavors found in coffee; coffee is much more than simply bitter. The wealth of flavors in specialty coffee is prized by consumers (Arnot, Boxall, & Cash, 2006), and the desire to experience these flavors has helped push the industry into its current renaissance. Given this, the need to quantify descriptive differences among various coffees along the production chain, from agronomy to brewing, led to the development of a reference-based lexicon (Chambers et al., 2016) and the hierarchal organization of that lexicon into the Coffee Taster's Flavor Wheel (Spencer, Sage, Velez, & Guinard, 2016). The coffee lexicon was created from the evaluation of over 100 different

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coffees from 14 different countries and comprises over 100 aroma and flavor attributes (Chambers et al., 2016). This flavor complexity stems from a wide variety of processing conditions throughout the production chain, including cultivar (Razafinarivo et al., 2013), various agronomic practices (Tolessa, D'heer, Duchateau, & Boeckx, 2017; Vaast, Bertrand, Perriot, Guyot, & Génard, 2006), postharvest processing (De Bruyn et al., 2017), roasting (Czerny & Grosch, 2000; Schenker et al., 2002), and brewing (Batali, Frost, Lebrilla, Ristenpart, & Guinard, 2020; Caprioli, Cortese, Sagratini, & Vittori, 2015; Fibrianto et al., 2019; Frost, Ristenpart, & Guinard, 2019), with each step impacting the final coffee flavor.

Despite much evidence that the brewing method helps govern which possible flavors will be expressed in a given coffee (Caporaso, Genovese, Canela, Civitella, & Sacchi, 2014; Frost et al., 2019; Gloess et al., 2013), there has been little systematic investigation. The most detailed work to date correlating the brewing indices of TDS and PE to sensory quality has focused on espresso coffee. Espresso often ranges from 5.0% to 10.0% TDS, while drip brewed coffee is much less (approximately 1.0% to 1.75%); the range for PE is similar, approximately 14.0% to 25.0%. When espressos were prepared at an equal brewing ratio but different grind setting, the coarsely ground coffee had lower TDS and PE and yielded espresso with increased acidity and aftertaste, lower odor intensity, but bitterness was not modified (Andueza, Paz De Peña, & Cid, 2003). In a further experiment, Andueza, Vila, De Peña, and Cid (2007) showed that increasing the brewing ratio increased the TDS and PE, while also increasing bitterness intensity. A more recent study comparing espresso and drip brew coffee reported espresso as having a higher intensity of bitterness, astringency, roasty, and overall aroma intensity versus the drip brew of the same coffee, with this perceived sensory difference driven in part by the strength disparity (TDS) of the two beverages (Gloess et al., 2013). Although it is clear from these studies that TDS and PE should impact the detailed sensory attributes of brewed coffee, to date the relationship between TDS and PE and the rich variety of possible sensory attributes in brewed coffee remains unclear.

In this study, a set of systematic experiments were performed to evaluate the effect of TDS and PE on the flavor profile of drip brewed coffee. A wet-washed coffee (*Coffea arabica*) was roasted to three different levels—light, medium, and dark—to provide three very different starting profiles. Descriptive analysis was then used to evaluate drip coffee brewed to a specific range of strength and extraction levels commonly found in commercial cafés worldwide, with three levels of TDS (1.00%, 1.25%, and 1.50%) and three levels of PE (16%, 20%, and 24%). The three TDS levels and three PE levels were combined in a factorial design for nine possible coffees, each brewed in triplicate. In all, the flavor profile of 27 unique coffees was measured. Response surface methodology (RSM) was then used to ascertain how each coffee descriptive attribute varied with TDS and PE.

2. MATERIALS AND METHODS

2.1 Coffee roasting and brewing

The study was designed to use the same green coffee roasted to three different levels, with each roast level then brewed to one of three TDS values and three PE values, using a full factorial design for a total of $3 \times 3 \times 3 = 27$ brewed coffees (Table 1). Green, wet-washed Arabica coffee was sourced from a single cooperative in Siguatepeque, Comayagua, Honduras and imported by Royal Coffee (Oakland, CA, USA). The three different roast levels were produced using a Loring S35 commercial scale roaster. Differences

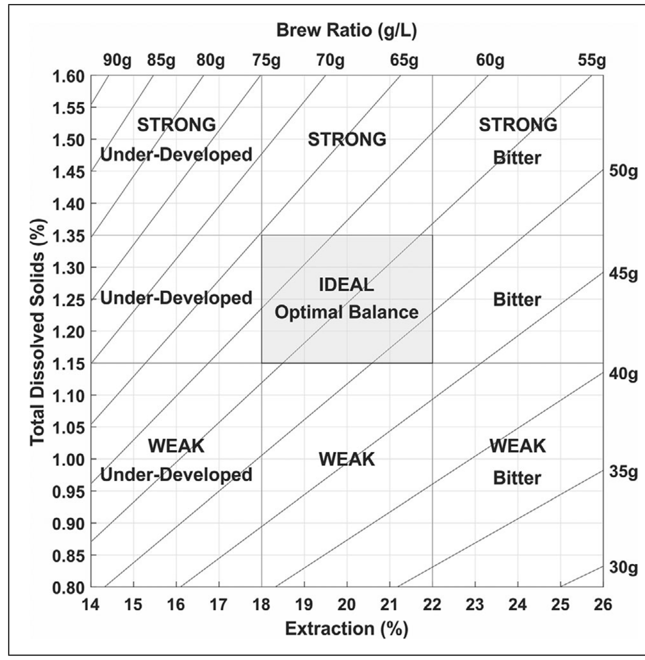

Figure 1–The Coffee Brewing Control Chart, showing the relationships among brew flavor and TDS, PE and yield. Reproduced from The Coffee Brewing Handbook (page 9), by T.R. Lingle, 2011, Specialty Coffee Association of America.

among the three roast levels were achieved by lengthening the development time (Figure 2), defined as the time from "first crack" until the coffee is expelled from the roasting drum onto the cooling tray. Figure 2 shows the temperature profiles, with first crack and drop indicated for each roast. Table 2 contains various parameters collected during the roasting of each coffee. After cooling, the roasted coffee was then packaged into 1-pound polypropylene aluminum laminate bags fitted with a one-way valve and then heat sealed. All three coffees were roasted and packaged within 2 hr. Coffee was then stored at −40 °C until 3 hr before brewing, when the coffee was thawed and brought to room temperature.

A programmable commercial brewer, Curtis G4 Single 1.0 Gal, # G4TP1S63A3100 (Wilbur Curtis Co., Monetbello, CA, USA) was used to brew all experimental coffees. Desired levels of TDS and PE were attained by altering three brewing parameters: brew ratio, water pulsing duty cycle, and number of water pulsing cycles. The latter two quantities allowed the total brew time to be varied, thus allowing more time for mass transfer to increase TDS, while keeping the total brew ratio at a desired value. The mass (3,075 g) and temperature (90.5 °C) of the brewing water were fixed throughout the experiment. Table 1 outlines the duration of each water pulse (on and off) and the number of cycles at each duty cycle to reach 3,075 g of water.

After the unground roasted coffee was removed from cold storage and allowed to reach room temperature, the coffee was then ground using a Mahlkönig Guatemala Lab Grinder set to the specific value indicated in Table 1. The particle size distribution (Figure 3) for each coffee at each of the three grind settings was measured in triplicate using a Sympatec HELOS/RODOS laser analyzer (Sympatec GmbH, Clausthal-Zellerfel, Germany) equipped with the Sympatec Vibir vibratory feeder and the R7 lens (18 to 3,500 μm). The coffee industry lacks standardized names for grinds of a specific particle size, but for the purpose of this work, we refer to the smallest grind with median particle

Table 1–Brewing parameters for each of the 27 experimental coffees.

Coffee	Roast	Target TDS	Target PE	Duty cycle (%)	No. of cycles	Brew ratio(g water/g coffee)	Grind setting
D-1.5-16	Dark	1.50	16	100	1	12.3	4
D-1.25-16	Dark	1.25	16	100	1	14.4	4
D-1.5-20	Dark	1.50	20	50	4	15.0	4
D-1.0-16	Dark	1.00	16	100	1	17.6	4
D-1.25-20	Dark	1.25	20	50	2	17.6	4
D-1.5-24	Dark	1.50	24	20	8	17.6	4
D-1.25-24	Dark	1.25	24	20	8	20.8	4
D-1.0-20	Dark	1.00	20	50	4	21.6	4
D-1.0-24	Dark	1.00	24	20	8	25.5	4
L-1.5-16	Light	1.50	16	83	2	12.2	5
L-1.25-16	Light	1.25	16	83	2	14.3	5
L-1.5-20	Light	1.50	20	50	4	14.8	4
L-1.0-16	Light	1.00	16	83	2	17.5	5
L-1.25-20	Light	1.25	20	50	4	17.5	4
L-1.5-24	Light	1.50	24	20	8	17.5	3
L-1.25-24	Light	1.25	24	20	8	20.6	3
L-1.0-20	Light	1.00	20	50	2	21.4	4
L-1.0-24	Light	1.00	24	20	8	25.4	3
M-1.5-16	Medium	1.50	16	83	2	12.2	5
M-1.25-16	Medium	1.25	16	83	2	14.3	5
M-1.5-20	Medium	1.50	20	50	4	14.8	4
M-1.0-16	Medium	1.00	16	83	2	17.5	5
M-1.25-20	Medium	1.25	20	50	4	17.5	4
M-1.5-24	Medium	1.50	24	20	8	17.5	3
M-1.25-24	Medium	1.25	24	20	8	20.6	3
M-1.0-20	Medium	1.00	20	50	4	21.4	4
M-1.0-24	Medium	1.00	24	20	8	25.4	3

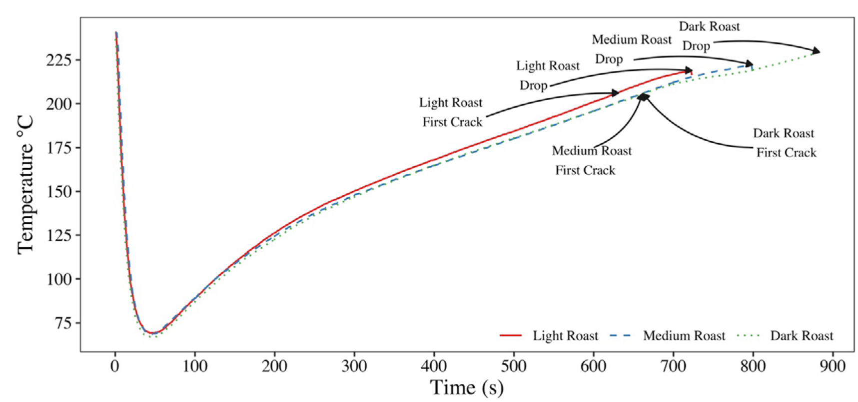

Figure 2–Temperature profile during the roasting of each coffee. Roast designation is indicated by: light roast in solid red; medium roast in blue dash; and dark roast in green dots. Time point of first crack and removal or "drop" of beans from the roaster are indicated.

Table 2–Roast profile parameters collected during roasting.

Roast	Initial mass (kg)	Final mass (kg)	Roast loss (%)	Initial temp (°C)	Final temp (°C)	First crack (°C)	First crack (s)	Development (s)	Overall (s)
Light	29.5	25.3	14.2%	240.8	218.9	206.1	631	92	723
Medium	31.7	26.9	15.1%	240.7	222.2	205.6	661	138	799
Dark	31.7	26.7	15.8%	236.9	229.4	205.6	662	171	883

size approximately 750 μm as "fine," the intermediate grind with median particle size of approximately950 μm as "medium," and the coarsest grind with median particle size approximately 1,100 μm as "coarse." We emphasize that these designations might differ from descriptions sometimes used qualitatively in the coffee industry. The grind sizes used here produced coffee at the target TDS and PE as outlined in Table 1, but note that only one grind setting was required to brew the nine dark roast coffees, whereas three settings were required to brew the light and medium roast coffees to the desired TDS and PE values (Table 1).

To brew, the ground coffee was then weighed into a brewing basket lined with a paper coffee filter. The basket/filter assembly was then inserted into the brewer, and a one-gallon vacuum-insulated, stainless steel, air pot was tared and placed below the outlet of the brew basket. The brewing program with specific water pulsing duty cycle was then started. After brewing, a

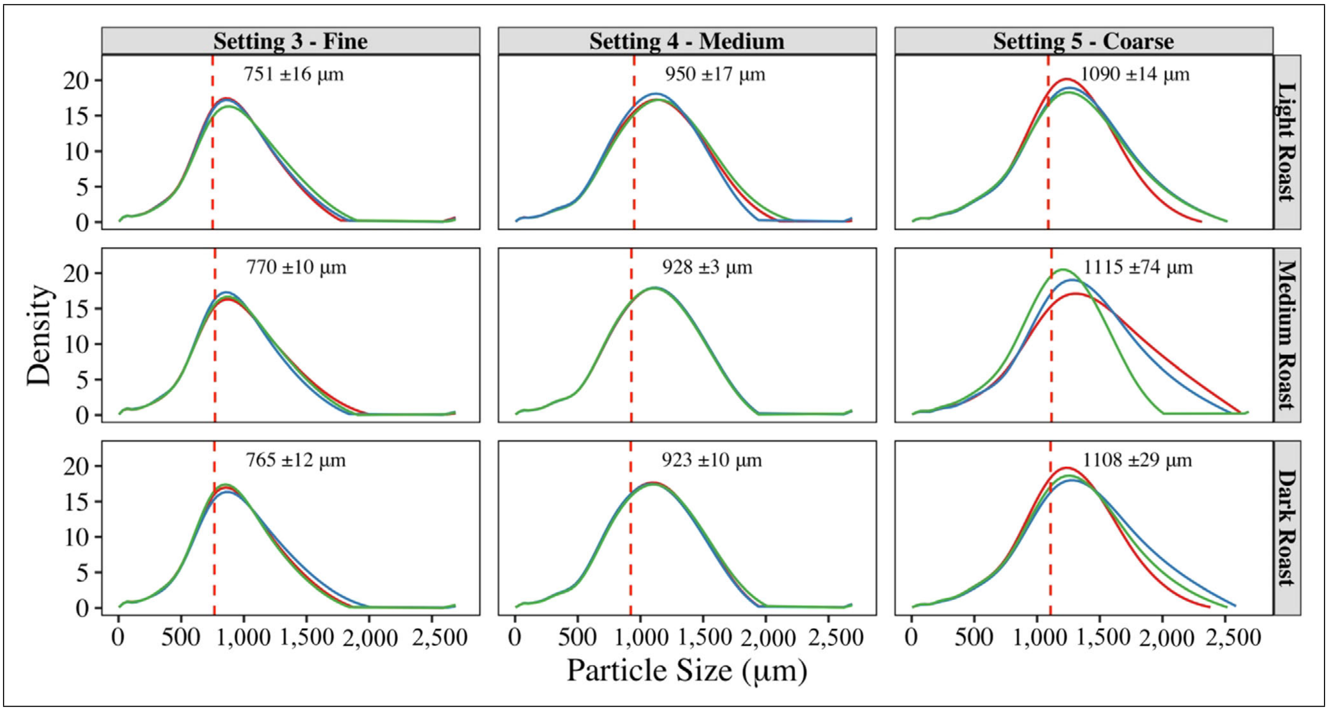

Figure 3–Particle size distribution for each coffee at three different grinder settings. Three replicates per treatment are differentiated by color. The dashed red lines indicate the median particle size, with corresponding value and standard deviation indicated at right.

3 min "drip out" period allowed the brewed liquid to finish draining from the bed of ground coffee. The brewed coffee mass was recorded, and the air pot was sealed with a lever pump.

2.2 Descriptive analysis

A descriptive analysis method that combined elements of the quantitative descriptive analysis and spectrum methods (Lawless & Heymann, 1998) was used to describe and quantify the flavor, aroma, and taste attributes of the 27 brewed coffees. All work with human subjects performed here was reviewed and approved by the UC Davis Institutional Review Board (IRB# 1082568). The trained panel was composed of 12 volunteers (nine females, three males, between the ages of 18 and 28 years), nonsmokers and regular coffee drinkers (at least one cup a day). Panelists were selected based on their interest and availability, but also correct completion of two triangle sets. The first triangle test was between dark roast and light roast, and the second compared high TDS versus low TDS. Each panelist attended seven training sessions over a 3-week period. During the initial three sessions, attribute generation was completed with the assistance of the Coffee Taster's Flavor Wheel (Spencer et al., 2016). Consensus terminology and reference standards (Table 3) were developed over the next three training sessions. Panel alignment was confirmed by in-booth testing and analysis of variance (ANOVA) of the preliminary data (not shown). Each panelist was then asked to complete 14 formal tasting sessions and evaluate 6 coffees in each session for 32 attributes. Individual, temperature-controlled, tasting booths lit with red light were utilized for all testing. Each coffee was presented in a 200 mL ivory-color ceramic mug of dimensions: 8 cm height, 7.5 cm opening dimeter, and 5.5 cm bottom diameter. The cup was filled to approximately100 mL and then allowed to cool to 65 °C. Within a single tasting session, the six coffees were presented in sequence with a 2-min rest between coffees. A randomized Williams Latin Square block design was used to control for possible carry over effects. Panelists were also provided with three unsalted crackers, a cup of water, and an empty cup to expectorate. Data were collected using the Red Jade data collection system (Red Jade Sensory Software Solutions, LLC, 2018). After logging in, panelists were served and instructed to begin scoring. Attributes were evaluated and scored on a 15 cm unstructured line scale. Measurements from the 15 cm line scale were then converted to a 100-point scale for data analysis.

2.3 Total dissolved solids and percent extraction

TDS was measured using a digital refractometer (VST, Inc.). A 75 mL sample of fresh brewed hot coffee was sampled into a 100 mL beaker and covered. The sample was allowed to cool to room temperature in a water bath. The refractometer was zeroed with room temperature deionized water. The room temperature coffee was stirred, and then analyzed. Independent calibration tests confirmed that the digital refractometer yielded TDS values consistent with an oven-drying technique to weigh the remaining dissolved solids after evaporation of the water (Batali et al., 2020). The PE was calculated as shown in Eq. 1 (Ristenpart & Kuhl, 2017):

$$\mathrm{PE} = \mathrm{TDS} \times \frac{m_{brew}}{m_{dry\ grounds}} \quad (1)$$

Descriptive analysis was completed with 258 individual brewed coffees. The measured TDS and PE for all brews are displayed in Figure 4 faceted by roast. The dashed lines represent the quality designations established on the traditional brewing control chart (Figure 1). Measured values of TDS and PE accurately represented the targeted treatment level, with ANOVA showing significant differences among the means of each TDS and PE levels (data not shown). The reported observations between beverage strength and

Table 3–Descriptive analysis attribute *definitions* or standards.

Standard	Preparation
Astringency	0.05% Alum solution, McCormick brand
Bitterness	0.05% Caffeine
Black pepper aroma	fresh ground black pepper
Black tea flavor	Lipton Black Tea
Blueberry flavor	1 tbsp, Private Selection Triple Berry Preserves
Brothy flavor	1 tsp Better Than Bouillon Seasoned Vegetable Base mixed with 2 tbsp water
Brown spice aroma/flavor	1 tsp each: ground cinnamon, ground nutmeg, clove, McCormick brand
Burnt wood/ash flavor	paper ashes, wood ash, 1 tbsp water
Cereal malt flavor	equal parts: General Mills Rice Chex, General Mills Wheaties, Quaker Quick Oats cereal, and Kretschmer Wheat Germ
Citrus flavor	fresh lemon juice diluted 1:1
Cocoa aroma	1/4 cup mixed into 3/4 cup MQ water, Hershey's Cocoa Powder Natural Unsweetened
Dark chocolate flavor	Lindt Excellence 90% Cocoa Supreme Dark Chocolate Bar
Dark green veg flavor	equal parts juice from: Green Giant Cut green bean, Del Monte spinach, Del Monte asparagus spears
Dried fruit flavor	1/8 cup Sun-Maid raisins and 1/8 cup prunes, all chopped and microwaved on high for 30 s with 1/4 cup MQ water
Earthy flavor	Miracle-Gro Potting Mix soil
Fermented flavor	Guinness Extra Stout beer
Flavor persistence	persistence of flavor after expectoration
Floral aroma	sweet, slightly floral/fruity, somewhat woody green associated with chamomile
Hay like flavor	McCormick Parsley Flakes
Molasses flavor	1/4 cup mixed into 3/4 cup MQ water, Grandma's Original Molasses (unsulphured)
Nutty aroma/flavor	roasted almonds
Roasted flavor	roasted peanuts
Rubber flavor	rubber bands
Smoke/acrid aroma	I drop ,Wright's Liquid Smoke Mesquite
Sourness	0.05% citric acid solution
Sweetness	1.0% sucrose solution
Sweet brown roast flavor	1 tbsp., C&H Pure Cane Sugar, Golden Brown
Thickness	the viscous feeling of the beverage as you press your tongue through it
Tobacco flavor	Camel cigarettes (Turkish and Domestic blend), 1 cigarette crushed
Woody flavor	popsicle sticks

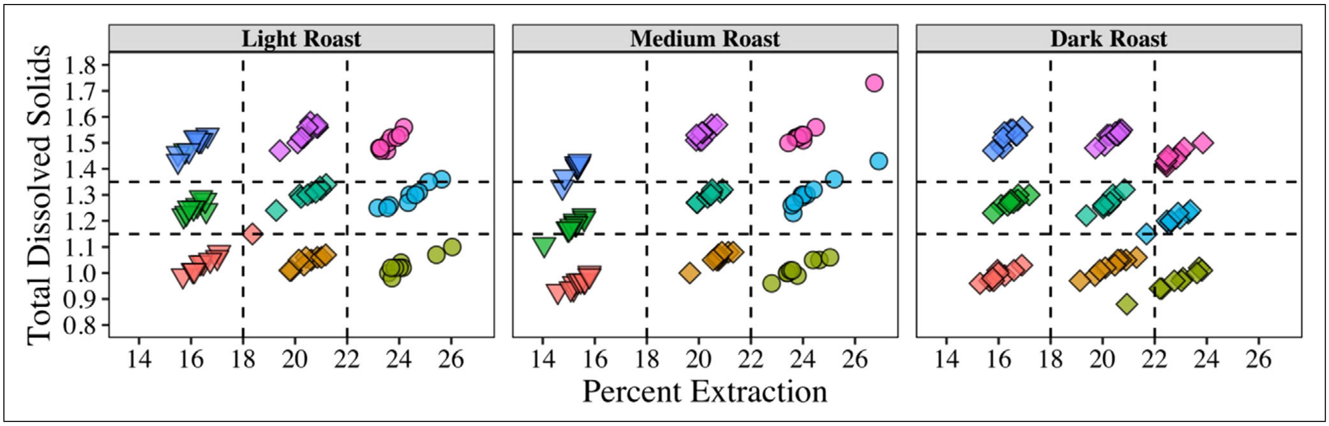

Figure 4–Measured TDS and PE for all brewed coffee. The dashed lines denote the dividers as shown on the traditional brewing control chart (Figure 1). Each targeted brewing index is represented by color and the shape represents the grind setting: triangle for "fine"; square for "medium"; and circle for "coarse."

grind are broadly consistent with previous work (Andueza et al., 2003, Frost et al., 2019).

2.4 Data analysis

2.4.1 Analysis of variance and principal component analysis. All statistical analyses were performed using R v3.5.2 "Eggshell Igloo" (R Core Team 2018) and the R Studio IDE v1.1.463. A significance of $\alpha = 0.05$ was set for all analyses. Descriptive sensory ratings were analyzed using a five-way fixed effect ANOVA model, with the main effects of judge, replicate, roast, TDS, and PE. In addition, the two-, three-, and four-way interactions for each main effect were also included. In the case where an effect was significant along with a significant equivalent effect by judge interaction, the F-statistic was calculated using the interaction mean square (Gay, 1998). For significant main effects, Tukey's least significant difference (LSD) was reported. PCA was applied to the covariance matrix of the significant descriptive attributes by each brewed coffee.

2.4.2 Response surface methodology. RSM was used to map the effects of TDS and PE to the sensory response. The full factorial design was based on two independent factors: TDS and PE, which were coded to levels of −1, 0, and 1 (cf. Eq. 2 and 3). The mean response intensity for each sensory attribute was averaged by sensory replicate, and then the regression analysis of the response was conducted by fitting a polynomial model using these mean values as shown in Eq. 4a and 4b. Here, $E(Y)$ is the

Table 4–Calculated *F*-ratios from five factor analysis of variance.

Factor	df	Astringent	Bitter	Black pepper aroma	Black tea flavor	Blueberry flavor	Brothy flavor	Brown spice aroma	Brown spice flavor	Burnt wood/ash F	Cereal malt flavor	Citrus flavor	Cocoa aroma	Dark chocolate F	Dark grn veg flavor	Dried fruit flavor	Earthy flavor
Judge	11	63.6*	72.8*	23.3*	99.9*	57.9*	35.9*	31.9*	115.2*	132*	192*	23.1*	32.9*	57.6*	76.0*	77.1*	80.7*
Rep	2	1.36	4.46*	1.58	3.61*	2.62	0.03	8.73*	1.51	2.02	0.11	6.31*	4.21*	8.78*	2.06	4.66*	1.31
Roast	2	4.00*	66.6*	5.39*	1.28	14.2*	0.40	1.80	7.08*	51.6*	1.96	22.4*	2.48	13.49*	0.40	7.84*	15.0*
TDS	2	11.9*	59.8*	0.11	0.91	1.43	0.23	0.98	0.57	18.4*	2.09	17.3*	0.5	0.45	2.51	3.74*	0.81
PE	2	1.03	13.8*	0.46	0.49	0.17	0.34	2.09	6.58*	18.0*	0.24	14.1*	2.83	5.16*	0.18	4.77*	8.18*
Judge:Rep	22	2.97*	4.00*	1.43	2.70*	1.86*	1.50	1.98*	1.38	3.05*	1.56	4.13*	2.99*	3.03*	3.82*	1.65*	4.02*
Judge:Roast	22	1.20	3.64*	1.57	1.64*	2.51*	0.56	1.24	1.60	1.89*	1.49	1.67*	0.55	1.50	2.44*	2.12*	1.50
Judge:TDS	22	0.81	3.54*	0.69	1.48	1.98*	1.62*	0.94	1.73*	3.01*	1.57	1.59	0.59	1.83*	0.90	3.02*	1.23
Judge:PE	22	1.38	1.36	1.11	1.80*	1.16	0.98	0.85	4.11*	3.60*	0.43	1.93*	0.98	1.28	2.21*	0.69	1.28
Rep:Roast	4	1.68	1.82	2.53*	0.25	1.19	0.61	0.45	0.91	0.63	0.22	0.96	1.04	0.37	0.53	0.82	1.02
Rep:TDS	4	0.97	1.78	0.54	0.78	0.45	0.49	0.35	0.35	1.04	0.54	1.81	1.03	1.23	2.55*	0.79	0.53
Rep:PE	4	0.38	1.03	1.44	2.26	1.40	0.32	0.33	2.34	0.41	3.19*	0.4	0.28	0.79	0.83	0.15	1.26
Roast:TDS	4	0.77	2.20	2.57*	0.34	2.24	0.41	0.52	1.28	0.53	0.15	2.97*	0.5	1.34	1.36	2.07	3.69*
Roast:PE	4	0.86	0.87	2.74*	1.99	0.96	1.33	0.60	1.37	1.15	2.10	0.99	0.07	0.94	0.90	0.41	0.83
TDS:PE	4	1.23	0.32	2.01	1.22	0.74	1.10	0.86	0.19	1.20	0.86	0.43	0.86	0.85	0.88	2.18	0.07
Judge:Rep:Roast	44	1.14	0.94	1.66*	1.26	1.00	0.97	0.80	0.86	0.94	1.31	1.47*	0.84	0.73	1.28	1.24	0.76
Judge:Rep:TDS	44	1.40	1.18	0.45	1.07	1.09	1.06	0.82	1.52*	1.19	0.79	0.96	0.95	1.28	1.25	0.94	0.99
Judge:Rep:PE	44	0.84	1.30	1.18	2.20*	1.08	0.79	0.48	0.63	1.37	0.74	0.64	0.75	1.01	0.81	0.63	1.05
Judge:Roast:TDS	44	0.93	1.11	1.09	1.19	1.53*	1.05	0.83	1.42	1.12	0.78	1.45*	0.76	1.00	1.33	1.61*	1.75*
Judge:Roast:PE	44	1.09	1.34	1.25	1.04	0.99	0.75	0.75	0.80	1.48*	1.71*	0.71	0.79	1.50*	1.47*	1.04	1.06
Judge:TDS:PE	44	0.62	0.74	0.97	1.05	1.11	0.88	0.70	0.73	1.25	0.98	1.15	0.58	0.70	1.46*	1.13	0.93
Rep:Roast:TDS	8	0.55	0.39	0.73	0.71	0.89	1.04	1.44	2.07*	1.09	0.82	0.99	0.17	0.46	0.77	1.44	1.75
Rep:Roast:PE	8	0.97	1.14	0.89	1.38	2.27*	0.80	0.46	1.45	0.38	0.50	0.97	0.71	0.84	0.81	1.37	1.04
Rep:TDS:PE	8	1.35	0.96	1.48	0.86	0.54	0.68	0.88	0.83	1.50	1.31	0.51	0.84	0.77	0.53	0.82	0.77
Roast:TDS:PE	8	1.33	0.57	0.95	1.31	0.94	0.90	0.53	2.13*	1.42	0.95	0.85	1.75	0.92	0.51	0.75	0.97
Judge:Rep:Roast:TDS	88	1.24	1.22	0.80	1.27	0.97	0.94	0.77	1.52*	0.97	0.89	1.28	1.00	1.54*	1.06	1.01	0.91
Judge:Rep:Roast:PE	88	0.70	1.23	1.36*	0.95	1.29	0.96	0.84	1.30	0.97	0.75	0.72	0.98	1.00	0.92	0.77	0.84
Judge:Rep:TDS:PE	88	0.97	1.01	1.03	0.81	0.77	0.96	0.6	0.83	0.94	1.24	0.72	0.81	1.08	1.05	0.76	1.22
Judge:Roast:TDS:PE	88	1.03	1.13	1.08	1.31	0.53	1.08	0.84	1.08	0.90	0.72	0.53	0.87	0.86	1.20	0.88	0.91
Rep:Roast:TDS:PE	16	1.01	0.86	1.02	1.26	1.05	0.65	0.73	0.91	1.10	1.04	0.96	0.69	0.53	1.41	1.30	0.73

(Continued)

Table 4–Continued.

Factor	df	Astringent	Bitter	Black pepper aroma	Black tea flavor	Blueberry flavor	Brothy flavor	Brown spice aroma	Brown spice flavor	Burnt wood/ash F	Cereal malt flavor	Citrus flavor	Cocoa aroma	Dark chocolate F	Dark grn veg flavor	Dried fruit flavor	Earthy flavor
Factor	df	Fermented flavor	Flavor persistence	Floral aroma	Hay-like flavor	Molasses flavor	Nutty aroma	Nutty flavor	Roasted flavor	Rubber flavor	Smoke/acrid aroma	Sour	Sweet	Sweet brown roast flavor	Thickness	Tobacco flavor	Woody flavor
Judge	11	29.5*	38.6*	48.7*	68.6*	72.5*	98.9*	156*	121*	12.8*	57.7*	110*	70.5*	287*	35.2*	227*	235*
Rep	2	0.28	0.29	5.79*	0.88	1.97	15.5*	6.31*	5.32*	2.63	5.10*	7.29*	3.16*	3.70*	1.82	7.07*	4.12*
Roast	2	4.60*	17.5*	4.52*	2.35	2.74	0.51	2.96	58.1*	18.9*	13.7*	64.1*	14.4*	16.9*	36.0*	3.88*	21.7*
TDS	2	5.65*	51.6*	0.31	1.50	2.71	1.32	1.28	5.27*	10.3*	0.20	77.4*	15.5*	1.48	18.7*	2.66	2.99
PE	2	1.14	7.78*	6.08*	0.82	0.21	0.71	0.46	6.23*	6.43*	0.39	29.7*	3.70*	10.7*	11.7*	0.09	0.71
Judge:Rep	22	3.59*	2.37*	3.54*	3.27*	1.70*	4.25*	2.52*	1.56	2.70*	3.00*	5.70*	3.95*	5.86*	1.56	4.44*	3.45*
Judge:Roast	22	2.43*	2.41*	1.92*	0.81	1.62*	1.42	0.90	3.36*	1.65*	0.89	1.44	3.48*	3.49*	3.28*	1.50	1.55
Judge:TDS	22	0.53	4.23*	1.75*	1.36	1.94*	1.14	2.12*	4.04*	1.50	0.71	3.75*	3.91*	2.69*	4.85*	1.89*	2.26*
Judge:PE	22	0.99	1.67*	1.91*	0.67	0.87	1.48	2.20*	1.09	1.74*	1.60	2.76*	1.12	1.72*	2.60*	1.88*	0.83
Rep:Roast	4	2.70*	1.45	0.54	3.72*	1.17	1.30	0.63	1.51	1.20	0.81	1.45	0.32	2.05	0.55	3.73*	0.24
Rep:TDS	4	0.39	1.46	2.66*	0.54	0.83	3.56*	0.98	1.15	1.56	0.52	1.63	1.28	2.32	0.73	0.19	1.61
Rep:PE	4	1.17	0.41	1.91	0.79	1.04	0.29	1.60	1.10	0.06	1.46	2.27	0.70	1.53	0.73	0.50	0.37
Roast:TDS	4	0.28	4.37*	0.36	3.15*	0.72	0.59	0.37	3.41*	1.04	1.17	8.25*	0.57	1.04	1.68	0.65	0.71
Roast:PE	4	0.47	1.12	0.46	0.36	0.88	1.40	2.52*	1.36	0.44	0.02	2.90*	1.34	2.16	0.32	0.42	0.44
TDS:PE	4	0.46	1.65	0.81	0.50	1.45	2.65*	1.77	1.25	1.58	0.71	0.42	0.44	2.82*	1.71	0.71	1.75
Judge:Rep:Roast	44	1.33	0.90	1.91*	1.07	0.78	1.62*	1.38	0.67	1.13	0.89	1.62*	1.99*	1.14	1.09	1.10	1.32
Judge:Rep:TDS	44	0.64	1.03	1.90*	1.02	1.03	1.41	1.62*	0.98	1.04	1.16	1.26	1.29	1.40	1.05	0.97	1.03
Judge:Rep:PE	44	0.87	0.76	1.20	1.02	0.53	1.29	0.43	0.84	1.29	1.02	1.69*	1.01	1.43	1.14	1.07	0.65
Judge:Roast:TDS	44	0.61	1.02	2.12*	1.05	0.98	1.81*	0.87	0.72	1.49*	1.42	1.66*	1.45*	1.95*	1.45*	1.15	1.53*
Judge:Roast:PE	44	0.75	1.59*	1.05	1.00	0.69	1.09	0.79	1.12	1.03	0.72	1.46*	1.34	1.35	0.94	1.59*	0.98
Judge:TDS:PE	44	0.73	0.82	0.86	1.53*	0.57	1.64*	0.76	1.09	1.22	0.91	0.75	1.37	2.24*	1.29	0.89	1.18
Rep:Roast:TDS	8	1.14	1.54	3.00*	1.41	1.59	0.61	1.90	1.69	1.49	2.49*	0.63	0.44	0.89	3.81*	1.45	1.58
Rep:Roast:PE	8	0.40	1.81	1.16	0.37	0.77	0.26	1.63	1.30	1.05	0.61	0.59	1.14	1.05	1.02	0.60	1.64
Rep:TDS:PE	8	0.64	0.77	0.56	0.92	1.33	0.45	2.08*	0.55	1.17	0.73	0.37	1.02	0.43	0.56	0.87	0.98
Roast:TDS:PE	8	0.71	0.49	1.18	0.48	1.17	0.97	0.25	1.01	0.92	0.86	1.20	0.55	1.21	0.69	0.49	0.91
Judge:Rep:Roast:TDS	88	1.11	1.09	2.37*	0.89	0.94	1.17	1.35*	0.65	1.32	1.28	2.01*	1.77*	1.16	1.27	1.13	0.83
Judge:Rep:Roast:PE	88	0.78	1.06	1.27	0.93	0.72	0.93	1.33	0.89	1.11	0.71	1.47*	1.53*	1.16	1.39*	1.10	0.84
Judge:Rep:TDS:PE	88	0.81	1.43*	0.97	1.00	0.87	0.88	1.09	1.08	1.11	0.86	1.25	1.14	0.95	1.06	0.88	0.73
Judge:Roast:TDS:PE	88	0.76	1.22	1.07	0.92	0.83	1.23	1.20	1.42*	1.68*	0.81	1.13	1.07	1.45*	1.13	0.77	0.98
Rep:Roast:TDS:PE	16	0.78	0.83	0.81	0.62	0.98	1.12	0.73	0.88	1.38	0.89	0.95	1.14	1.33	0.97	0.68	0.46

* – Indicates a significant F-ratio at $P < 0.05$.

predicted response, β_0 is a constant, β_1, β_2, β_{11}, β_{22}, and β_{12} are the regression coefficients, and x_1 and x_2 are the levels of coded independent variables.

$$x_1 = \frac{PE - 20}{4} \tag{2}$$

$$x_2 = \frac{TDS - 1.25}{0.25} \tag{3}$$

$$\text{First Order : E}\,(Y) = \beta_0 + \beta_1 x_1 + \beta_2 x_2 \tag{4a}$$

$$\begin{aligned}\text{Second Order : E}\,(Y) &= \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 \\ &\quad + \beta_{11} x_1^2 + \beta_{22} x_2^2\end{aligned} \tag{4b}$$

Model adequacy was evaluated through the Fisher's test (F-statistic) and the lack of fit (Box & Draper, 1987). The first-order model was initially fit, and if significance was shown, the interaction and second-order terms were then added. If one or more of the higher order model terms were significant, then the full second-order model was retained. The intensity for each sensory attribute was fit to each individual roast, and also fit irrespective of roast. Finally, the RSM was carried out using R v3.5.2 "Eggshell Igloo" (R Core Team 2018) and the R Studio IDE v1.1.463.

3. RESULTS AND DISCUSSION

3.1 Analyses of variance

F-ratios calculated from the five-factor ANOVA are found in Table 4. An additional three-factor ANOVA, using the 27 individual *Coffees*, *Judges*, *Replications*, and their two-way interactions, which was conducted for the purpose of assessing panel performance is reported in Supplemental A. The examined F-ratios, in either ANOVA, show a consistent ability of the panel to discriminate the coffees and experimental factors: *Roast*, TDS, and PE. There were instances of significant replication, judge by replication, and judge by coffee (or coffee subfactor) F-ratios for a few of the attributes, but not the majority. Most importantly, we feel that none of these effects obscured the sensory differences among the coffees, which were the focus of the descriptive analysis.

The trained panel found significant differences by roast for 20 attributes, by TDS for 10 attributes, and by PE for 13 attributes (Table 4). Mean intensity for each significant attribute by experimental factor level is shown in Figure 5, with post hoc LSD significant differences indicated with letters. Supplemental B presents a complete means table for all evaluated attributes by factor. Differences by roast were significant for 16 descriptive attributes, differences by TDS were significant for 8 attributes, and differences by PE were significant for 13 attributes (Figure 5). Increasing roast level from light to dark yielded increased *astringency*, *bitterness*, *brown spice flavor*, *burnt wood/ash flavor*, *dark chocolate flavor*, *earthy flavor*, *rubber flavor*, *smoke/acrid flavor*, *thickness*, *tobacco flavor*, and *woody flavor*. In contrast, darker roasts yielded decreased intensities of *blueberry flavor*, *citrus flavor*, *dried fruit flavor*, *sweet brown roast flavor*, and *sweetness*. Increased TDS values, independent of roast or PE, caused increased *astringency*, *bitterness*, *burnt wood/ash flavor*, *citrus flavor*, *dried fruit flavor*, *fermented flavor*, *rubber flavor*, and *thickness*. Notably, *sweetness* was the single attribute to decrease with

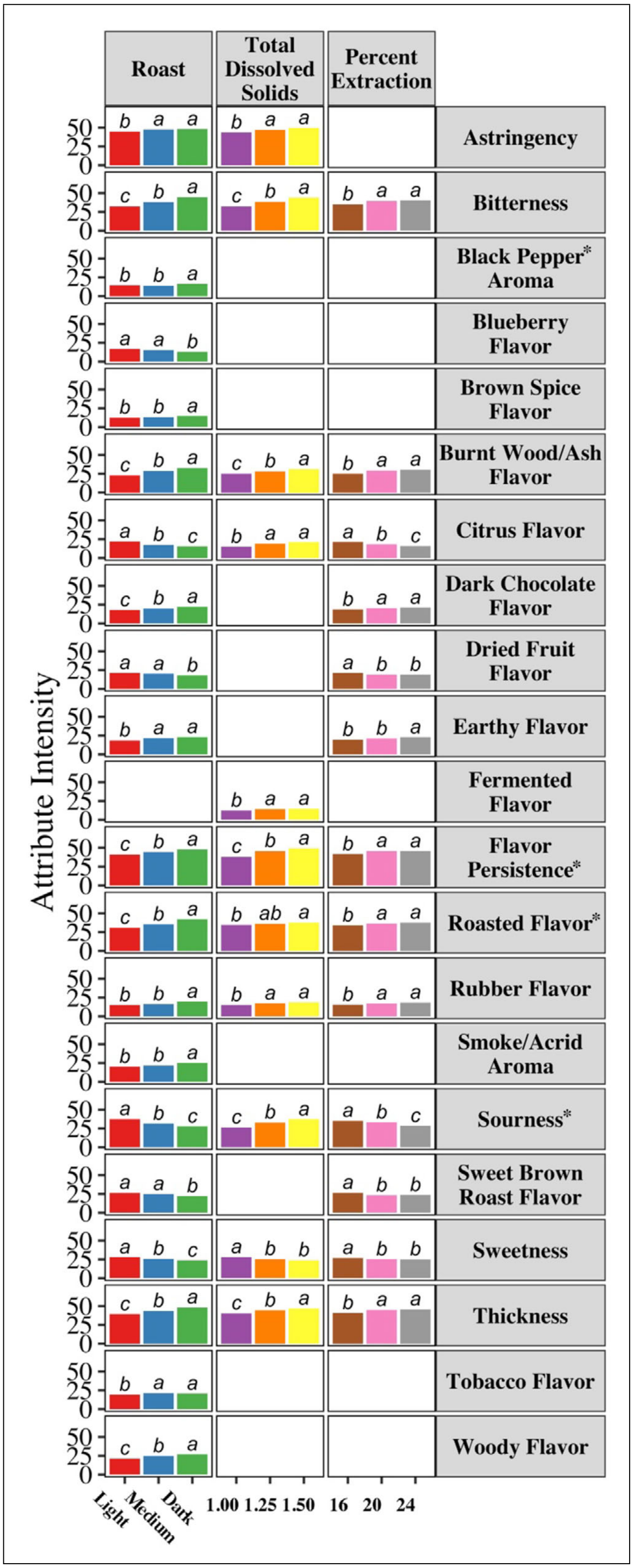

Figure 5–Mean attribute intensities for each factor are indicated by column height. Fischer least significant differences (LSD) are designated by letters within each attribute–factor panel; if two columns show the same letter, they are not significantly different. Sensory attributes showing no statistically significant trend were left blank. Asterisks indicate attributes that exhibited a significant interaction (Figure 6).

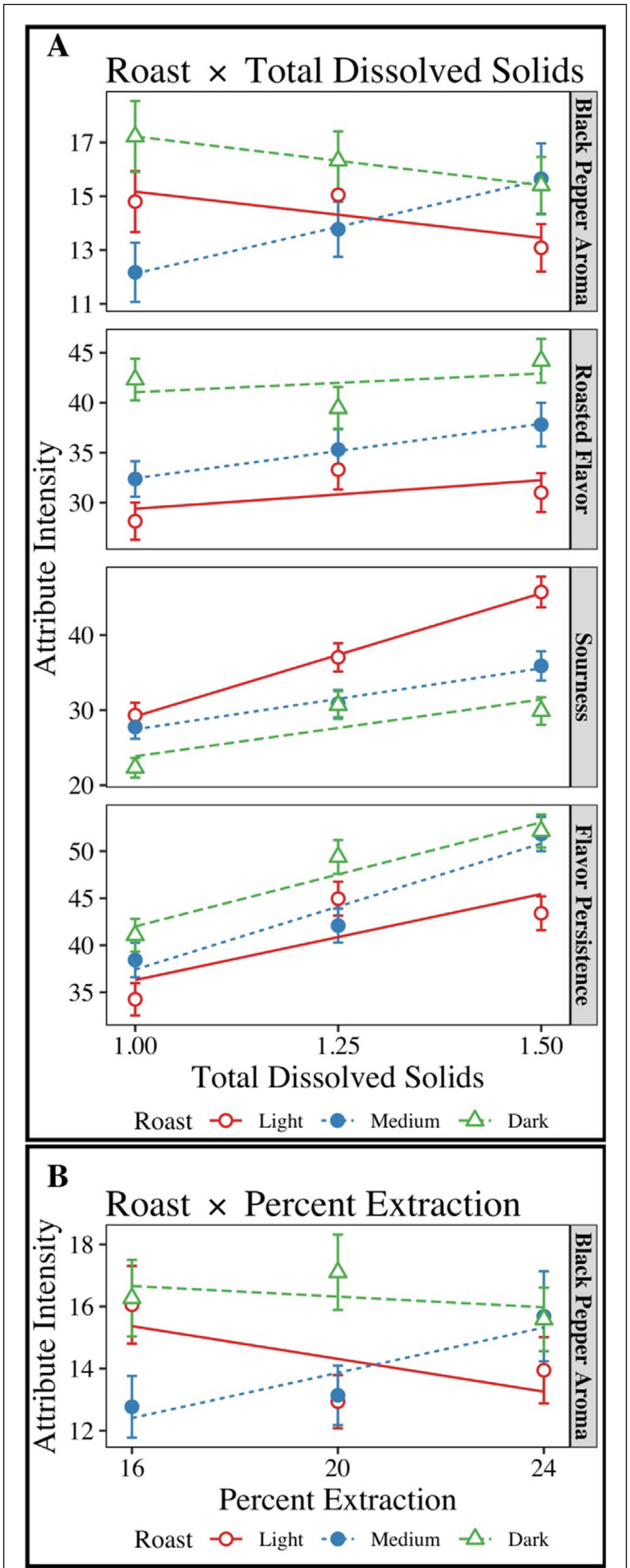

Figure 6–Mean intensity by significant interaction for descriptive attributes. A linear fit is applied to each roast as indicated: light roast in red, with open circles; medium roast in blue dash, with closed circles; and dark roast in green dash, with open triangles. Standard error of the mean is shown by error bar. Panel A displays the roast by TDS interactions, and panel B displays the roast by PE interactions.

increasing TDS, regardless of roast or PE. Of the 13 attributes impacted by PE, irrespective of roast level or TDS, nine increased with PE: *bitterness*, *burnt wood/ash flavor*, *dark chocolate flavor*, *earthy flavor*, *flavor persistence*, *roasted flavor*, *rubber flavor*, and *thickness*. A decrease in PE yielded a reduced intensity of *citrus flavor*, *dried fruit flavor*, *sweet brown roast flavor*, *sourness*, and *sweetness*.

Significant interactions between each experimental factor were further evaluated in Figure 6. A significant roast × TDS interaction was shown for four attributes: *black pepper aroma*, *roasted flavor*, *sourness*, and *flavor persistence* (Figure 6). *Sourness* and *flavor persistence* increased with increasing TDS, but the rate of increase was modified by roast. Coffees brewed with the light roast coffee were significantly more sour at all TDS levels when compared to the medium and dark roast brewed coffees. This sour increase is visualized in Figure 6 as the light roast (red solid line) is positioned above the dark (green long-dash line) and medium (blue short-dash line) roast. Additionally, the light roast shows a significantly greater slope versus the dark or medium roast, but the dark and medium roast show an equivalent rate of sour intensity increase. *Flavor persistence* also showed a general increase with increasing TDS. Coffees brewed with the dark roast showed the highest intensity of *flavor persistence* across the TDS range, but differences in the rate of increase by roast were minimal.

Black pepper aroma and *roasted flavor* did not show a general trend of increasing or decreasing intensity among the three roasts levels with respect to TDS. *Roasted flavor* showed increasing intensity when comparing among the three roast levels (Figure 6); coffees brewed with the dark roast had the most intense *roast flavor*, followed by the medium and then the light roast brews. The *roast flavor* intensity showed minimal differences with increasing TDS. *Black pepper aroma* decreased in intensity with increasing TDS in coffees brewed with the light or dark roast coffee, but the intensity increased with increasing TDS when evaluated in coffees brewed with the medium roast coffee (Figure 4). *Black pepper aroma* was also found to have a significant interaction between roast and PE, but without a clear trend among the evaluated factors.

3.2 Principal component analysis

Principal component analysis (PCA) was applied to the mean ratings of the 21 significant descriptive attributes across the 27 specific brewed coffees. The first two principal components accounted for 84.3% of the variance in the original variables (Figure 7). The score plot of the 27 coffees is shown in Figure 7A, and the loadings are plotted in Figure 7B. Roast level separates the coffee along the first component; the nine dark roast coffees are found to the right, and nine light roast coffees to the left. The nine coffees brewed with the medium roast are found between the light and medium roast coffees, generally positioned along a diagonal running from quadrant III to quadrant I. The dark roast coffees were associated with *flavor persistence*, *bitterness*, *thickness*, *burnt wood/ash flavor*, and *roasted flavor*. In contrast, the light roast coffees were associated with *sourness*, *citrus flavor*, *dried fruit flavor*, *sweet brown roast*, and *sweetness*. The effect of PE also discriminated the coffees along the first component, but the effect was not as strong as the roast effect.

The coffees were positioned by increasing TDS through a diagonal line bisecting quadrants II and IV, and passing through the plot origin. Coffees brewed to 1.00% TDS were associated with *sweetness* and were positioned in the quadrant III. Coffees brewed to a TDS of 1.25% were found along the diagonal, but coffees with a 1.50% TDS were positioned to the right of that diagonal associated with *astringency*, *flavor persistence*, and *bitterness*.

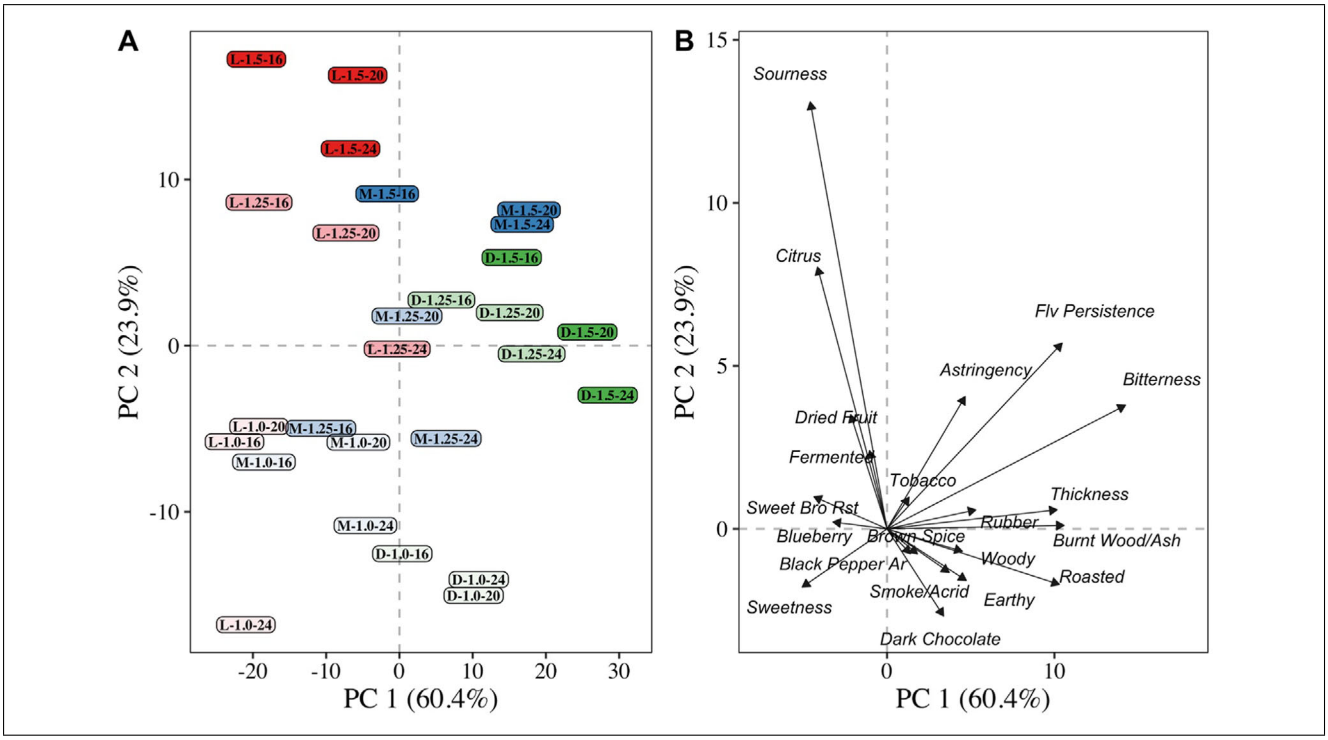

Figure 7–Principal component biplot showing brewed coffee (A) and significant descriptive attributes (B). Roast profile is indicated with color: light roast in red; medium roast in blue; and dark roast in green. The color intensity represents the TDS.

3.3 Response surface modeling

RSM was applied by roast to the 21 significant attributes, from which 16 attributes produced 34 significant response surfaces (Figures 8 and 9). *Burnt wood/ash flavor*, *citrus flavor*, *sourness*, *bitterness*, *sweetness*, *thickness*, and *flavor persistence* each returned fits for all three roast levels (Figure 8; see also Supplemental C for three-dimensional renderings of the response surfaces). The intensities of *burnt wood/ash flavor*, *bitterness*, *thickness*, and *flavor persistence* each increased with increasing PE and TDS (Figure 8), with the highest intensity of each attribute found at the highest level of PE and TDS. The intensity of *burnt wood/ash flavor* showed an increasing dependence to TDS as the roast level increased, which is evidenced by the ascent becoming more strongly related to TDS as the roast becomes darker. *Bitterness* and *flavor persistence* were also strongly driven by TDS among the three roast levels, with the dark roast showing the greatest dependence on TDS.

Citrus flavor and *sourness* were each described by a linear response for the light roast and medium roast, but a second-order fit best described the dark roast profile. The two sensations were similar in that the highest *sour* and *citrus* intensities were perceived at the highest TDS and lowest PE. The intensity of *sourness* increased at a steeper ascent as compared to the *citrus* intensity.

Seven additional attributes were also fit with linear response surfaces (Figure 9), but for each attribute, significance was not found across the three individual roast levels. Significant fits were shown for *astringency*, *earthy flavor*, *fermented flavor*, and *rubber flavor* for the light roast coffee. *Astringency* and *fermented flavor* were clearly influenced by changes in TDS, in contrast to *earthy flavor's* heavy dependence on PE. Also, *rubber flavor* showed a significant response for the light roast that increased with increasing TDS and PE. *Black pepper flavor*, *blueberry flavor*, *brown spice flavor*, *dark chocolate*, *earthy flavor*, *roasted flavor*, and *rubber flavor* were fit with a response surface for the medium roast coffee (Figure 9). *Rubber flavor*, *roasted flavor*, *earthy flavor*, *brown spice flavor*, and *black pepper aroma* all increased with increasing PE and increasing TDS. This was contrasted with *blueberry flavor*, which showed the greatest intensity at low PE and low TDS. *Dark chocolate* was unique in that the highest intensity was found at the highest PE but lowest TDS. Finally, the dark roast was fit with a response surface to describe *astringency*, which showed increasing intensity with increasing PE and TDS.

Inspection of Figures 8 and 9 suggests that many of the sensory attributes behave similarly with respect to TDS and PE regardless of the roast level. To probe this behavior further, we calculated a new series of response surfaces by removing roast as a blocking factor—in effect, averaging over the roast level. This procedure yielded 13 significant response surfaces (Figure 10). Eight of the attributes exhibited peak intensities at high TDS and high PE: *astringency, bitterness, burnt wood/ash, earthy, flavor persistence, roasted flavor, rubber flavor*, and *thickness*. Four of the attributes exhibited peak intensities at high TDS but low PE: *citrus flavor, dried fruit flavor, fermented flavor*, and *sourness*. Only one attribute—*sweetness*—exhibited a peak intensity at low TDS and low PE.

4. Discussion

The study yielded several key findings. First, regardless of roast level, several sensory attributes displayed similar dependencies on TDS and PE; for example, the three primary taste sensations of *sweetness*, *sourness*, and *bitterness* each exhibited their highest intensity at a different position within the TDS/PE response surface, but the location of the highest intensity was similar for each attribute across roast levels (Figure 8). Regardless of roast level, *bitter* intensity increased with both TDS and PE; *sourness* increased with TDS but decreased with PE; and *sweetness* decreased with both TDS and PE. Similarly, *citrus flavor*, *burnt wood/ash flavor*, *thickness*, and *flavor persistence*, each showed a similar response surface among the three roast levels. These seven attributes were essential to the

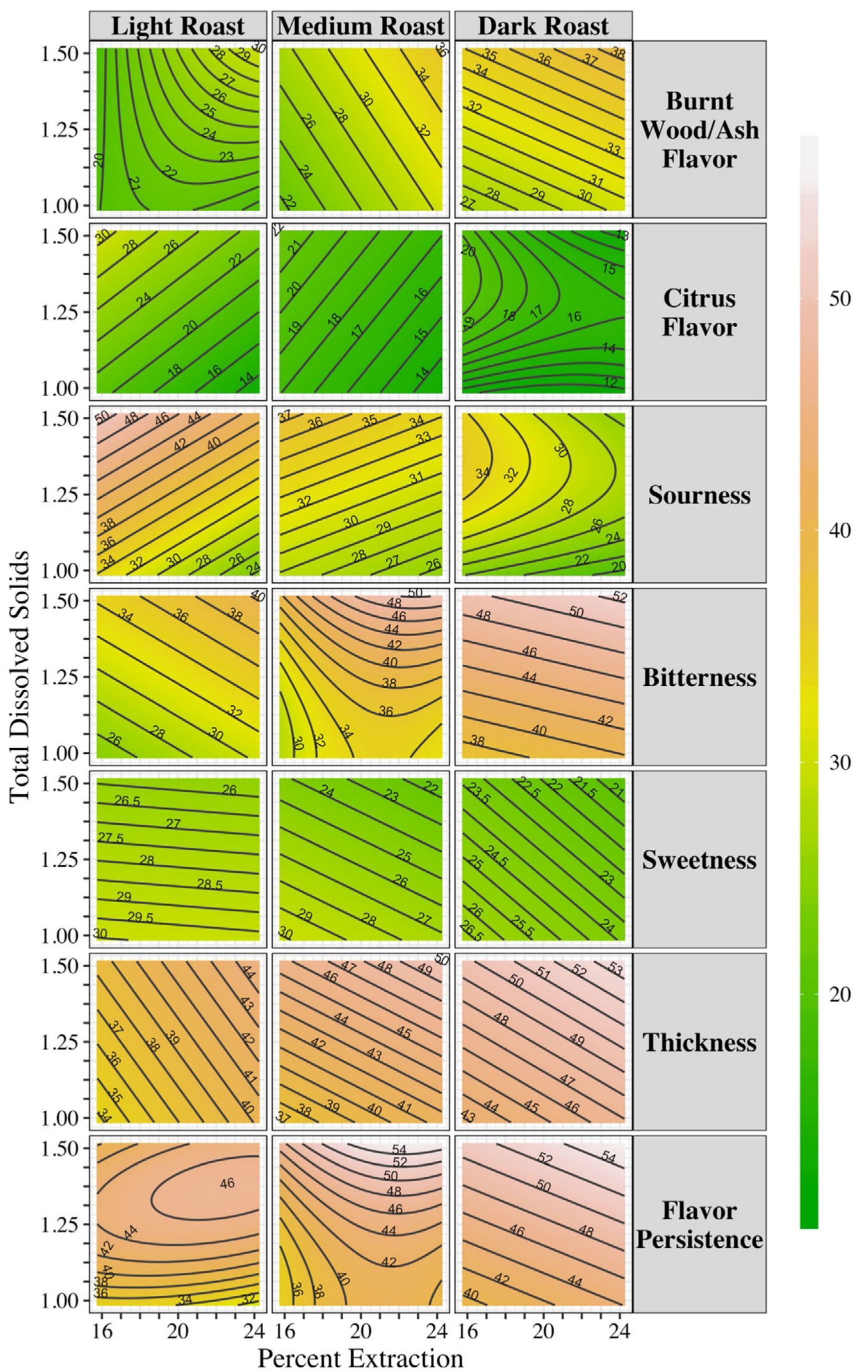

Figure 8–Contour plots, by roast level, of the fitted response surfaces for attributes that exhibited significant variation versus TDS and PE for all three roast levels.

flavor profile of the experimental coffee, and they could serve as fundamental markers to guide brewing to achieve a specific flavor profile.

A second key finding showed the relationship between roast level and brewing. Not surprisingly, the level of roast modified the flavor intensity of all but 3 of the 16 significant sensory attributes (Figure 5). However, the flavor and aroma intensity of a given attribute could be increased or decreased depending on how the coffee was brewed. Furthermore, as shown in Figures 8 and 9, each attribute shared at least one position of equivalent intensity across the three roasts; for example, overall *bitterness* increased with roast, but a *bitter* intensity of 40 was found on the response surface of all three roast levels. In effect, roast acted as a coarse flavor adjustor, while brewing provided a way to fine tune the flavor profile.

Notably, the intensities of citrus flavor and sourness both decreased with roasting and were most intense at high TDS and low PE. The perception of citrus flavor and sourness was likely driven by highly soluble organic acids, which are formed and subsequently degraded during roasting (Ginz, Balzer, Bradbury, & Maier, 2000). Overall sweetness was also shown to decrease with increased roasting, and the highest intensity of sweetness was found at low PE and low TDS. Brewed coffee does not appear to have sufficient sugar content to stimulate sweetness (Batali et al., 2020), and thus the perception of sweetness likely is a result of the

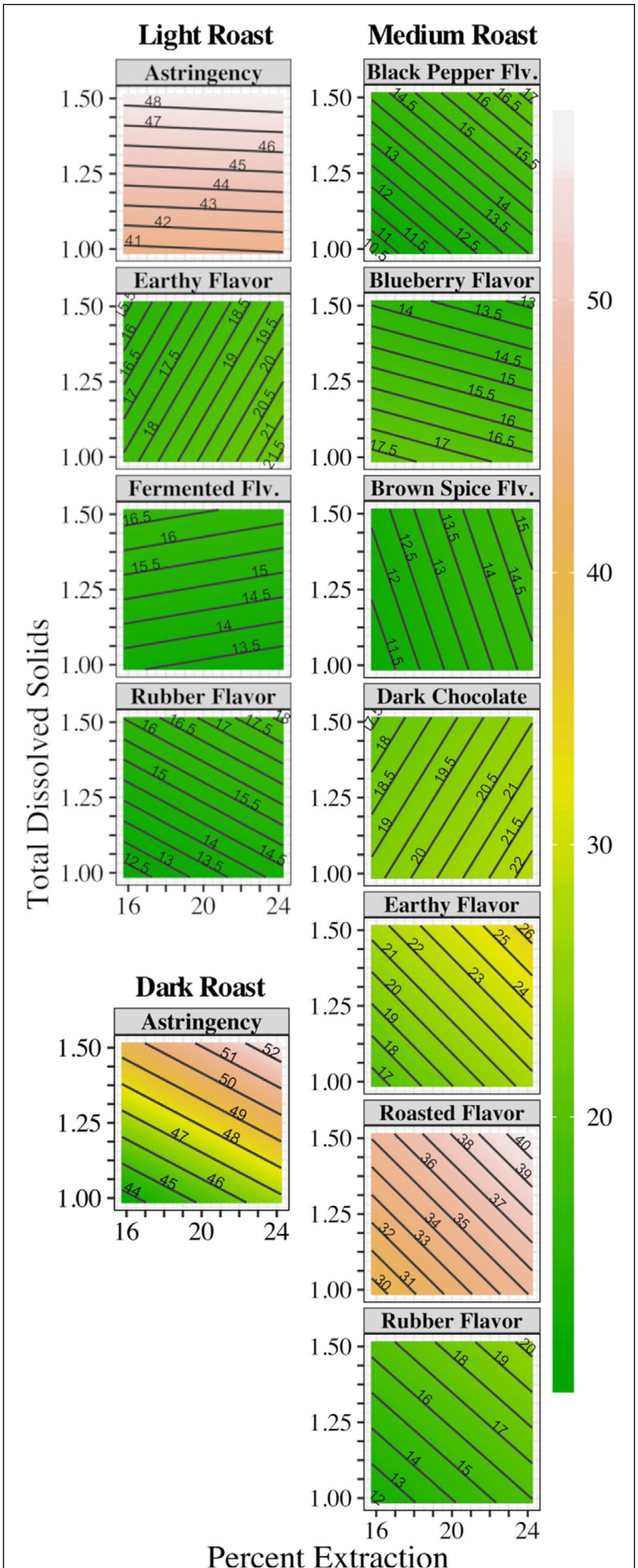

Figure 9–Contour plots, by roast level, of the fitted response surfaces for attributes that exhibited significant variation versus TDS and PE for some but not all of the roast levels.

flavors associated with sweetness: blueberry flavor, sweet brown roast flavor, dark chocolate, and dried fruit (Spence, 2010). These flavors would be masked by the increasing bitterness that would result from increasing TDS and PE, and concentration changes from brewing.

In contrast, thickness displayed the opposite trend from sweetness, increasing at high PE and high TDS. Thickness also increased with roast level (Figure 8 and Supplemental C). Thickness was defined by the panel as "the viscous feeling of the beverage as the panelist passed their tongue through it [the coffee]." The increase with respect to TDS likely results from an increase in physical and perceived viscosity known to result at higher concentrations of dissolved solids in coffee (Pangborn, Gibbs, & Tassan, 1978). In contrast, the mechanisms for the observed increases in thickness with respect to PE and roast level are less clear. One possible explanation is that our experimental design carefully controlled for the amount of TDS, but it did not explicitly control for the amount of nondissolved solids and oils in the brew. Darker roast levels are well known to yield more oil, so it is possible that the increase in thickness with roast level was associated with a larger fraction of emulsified oil droplets present in the dark roast brews. Similarly, to achieve higher PE values at constant brew ratio and TDS, we necessarily varied the total brew time and the grind size (Table 2). Even though the TDS was held constant, it is possible that the amount of non-dissolved solids (i.e, micron-scale colloids) was larger at higher PE values because of the smaller grind size used in general at higher PEs. Alternatively, it is possible that the varied chemical compositions associated with roast levels, for example, an increase in the concentration of melanoidins resulting from Maillard reactions, or varied chemical compositions with respect to PE, for example, relative ratio of highly to weakly soluble molecules, might also have affected mouthfeel. Further research would be necessary to determine the relative contributions of nondissolved solids, emulsified oils, and chemical composition to the mouthfeel of coffee.

Finally, it is interesting to note that flavor persistence showed a stationary point on the light roast surface (22.6% extraction and 1.37% TDS). Panelists defined flavor persistence as the "persistence of flavor after expectoration." Although not defined to a specific flavor/taste, it is likely that panelists were reacting to the temporal persistence of bitterness and astringency, which has been evaluated in various other products (Frost, Blackman, Ebeler, & Heymann, 2018, Ng, et al., 2012).

A third key result is that for a given roast level, changes in brewing did not significantly affect the intensity of several attributes, including *smoke/acrid aroma*, *tobacco flavor*, or *woody flavor*. Additionally, the highest intensity of *rubber flavor* was found in the dark roast coffees, but a significant response surface was only obtained for light and medium roast; thus, all dark roast coffees were perceived to have the same intensity of *rubber flavor*, but *rubber flavor* could be modified in the light and medium roast coffees by brewing. These four attributes (*smoke/acrid aroma*, *tobacco flavor*, *woody flavor*, and *rubber flavor*) are common descriptors of dark roast coffee, and their impact on consumer preference has previously been shown (Frost et al., 2019).

Taken together, our results suggest that the Coffee Brewing Control Chart (Figure 1) could be updated significantly. Our data clearly show that brewing to different TDS and PE levels significantly impacts multiple sensory attributes, regardless of roast level, indicating that Lockhart's original idea of organizing sensory data versus TDS and PE is well posed. Our data do not support, however, the current demarcation of nine brewing zones in the

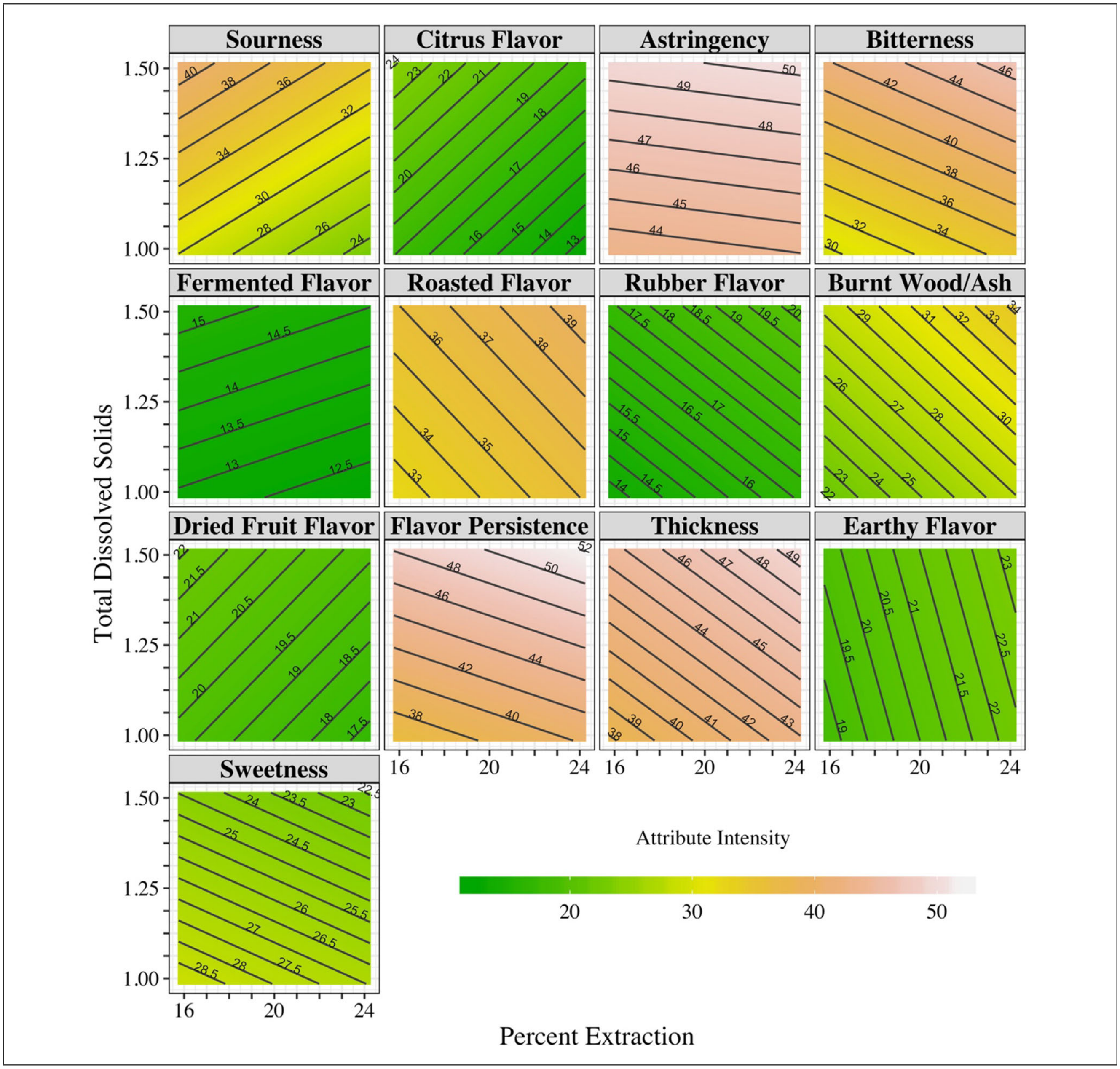

Figure 10–Contour plots of the fitted response surfaces for attributes that exhibited significant variation versus TDS and PE, when roast level is removed from the analysis as a blocking factor (i.e., averaging over roast level).

chart. Most importantly, some attributes actually became stronger at lower TDS, so the current vertical demarcation of "strong" and "weak" versus increasing TDS is potentially misleading. Moreover, our sensory data show that the sensory attributes follow a continuous progression with TDS and PE, with no abrupt transitions in intensity at particular PE values; this result suggests the current horizontal delineation in the Brewing Control Chart (e.g., "bitter" above 22% PE) is also potentially misleading. Instead, a more nuanced Brewing Control Chart would perhaps be most similar to Figure 10, which shows how several specific sensory attributes vary with TDS and PE regardless of roast level.

We also emphasize that all data reported here were based on a single type of wet-washed coffee, chosen to represent a standard "clean" coffee. Although prior work has indicated that roast level has a greater impact on the flavor profile than the variety of green coffee (Bhumiratana, Adhikari, & Chambers, 2011), many specialty coffees are famous for more exotic flavor profiles. For example, coffees from Burundi are noted for their intense blueberry aroma, while Panamanian Geishas are famous for their tea-like and floral notes (Hoffmann, 2017). Such specialty coffees presumably would exhibit qualitatively similar trends to those reported here, but further research is necessary to corroborate that hypothesis quantitatively and to further identify how the desired specialty characteristics vary with TDS and PE.

Finally, perhaps the most distinguishing feature of the current Brewing Control Chart is the "ideal" zone in the middle of the chart. We emphasize that here we report only sensory descriptive data, so it is unclear whether or not consumers indeed prefer coffees brewed to the ostensibly "ideal" TDS and PE. More detailed consumer preference studies are necessary to address that question.

5. CONCLUSIONS

This study examined the rich variety of flavors and mouthfeels that can be produced in drip brewed coffee by modifying roast, strength, and yield. The majority of these flavors and mouthfeels were shown to increase with both TDS and PE, while several increased with TDS but decreased with PE. One particularly important sensory attribute—*sweetness*—decreased with both TDS and PE, regardless of roast level. The results suggest that the classic Coffee Brewing Control Chart should be updated to reflect the complex behavior of the sensory attributes with respect to the brewing parameters.

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AUTHOR DISCLOSURES

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AUTHOR CONTRIBUTIONS

Study design, result interpretation, and manuscript writing were done by all authors. Data collection and analysis was performed by Scott Frost.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Supplemental A: Calculated *F*-ratios for three-factor ANOVA.

Supplemental B. Mean attribute intensity by factor.

Supplemental C: Three-dimensional rendering of Figure 8.