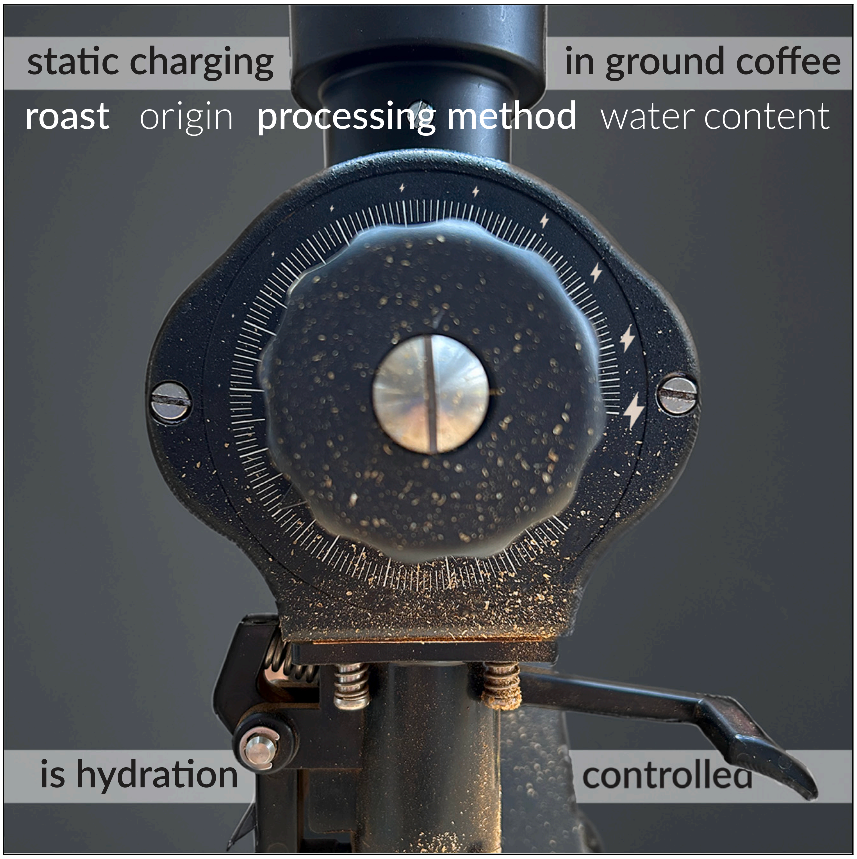
Matter

CellPress
OPEN ACCESS

Article

Moisture-controlled triboelectrification during coffee grinding



Triboelectrification is a physical process that causes static charge accumulation on material surfaces. During coffee grinding, coffee particles tribocharge, causing particle aggregation. These aggregates pose challenges for preparing reproducibly tasty espresso. We demonstrate that whole-bean coffee charging primarily depends on the moisture content of the beans themselves. Through control of the humidity and by adding extrinsic water, we demonstrate control over the extent of tribocharging, resulting in increased mass extraction, and posit opportunities to improve coffee preparation reproducibility.

Joshua Méndez Harper, Connor S. McDonald, Elias J. Rheingold, ..., Yong-Hyun Kim, Josef Dufek, Christopher H. Hendon

jmendez7@uoregon.edu (J.M.H.)
chendon@uoregon.edu (C.H.H.)

Highlights

Identifying the coffee properties that govern triboelectric polarization of coffee

Whole-bean moisture content below 2% causes negative particle charging

External water passivates surface charging but does not create clumping

With fixed espresso brew parameters, charge reduction increases coffee extraction

3 **Understanding**
Dependency and conditional studies on material behavior

Méndez Harper et al., Matter 7, 1–18
January 3, 2024
Published by Elsevier Inc.
https://doi.org/10.1016/j.matt.2023.11.005

Please cite this article in press as: Méndez Harper et al., Moisture-controlled triboelectrification during coffee grinding, Matter (2023), https://doi.org/10.1016/j.matt.2023.11.005

Matter

CellPress
OPEN ACCESS

Article

Moisture-controlled triboelectrification during coffee grinding

Joshua Méndez Harper,[1,*] Connor S. McDonald,[2] Elias J. Rheingold,[2] Lena C. Wehn,[2] Robin E. Bumbaugh,[2] Elana J. Cope,[2] Leif E. Lindberg,[2] Justin Pham,[2] Yong-Hyun Kim,[3] Josef Dufek,[1] and Christopher H. Hendon[2,4,*]

SUMMARY

Granular materials accumulate surface charges through triboelectrification and fractoelectrification—charging resulting from material friction and fracture, respectively. These processes occur during coffee grinding and impact coffee production at both the enthusiast and industrial-length scales. By sourcing commercially roasted coffee as well as roasting our own, we find that roast color and grind coarseness impact the charging; fine, darker roasts acquire charge-to-mass ratios comparable to those inferred from particles in volcanic plumes and thunderclouds. Furthermore, we elucidate the influence of residual internal moisture on electrification, concluding that moisture can tune both the magnitude and polarity of charge. In addition to possible technological applications, we demonstrate that the addition of external water simultaneously suppresses surface charging and clumping of ground coffee and results in notably different flow dynamics in espresso formats, likely yielding markedly different taste profiles and more concentrated extracts.

PROGRESS AND POTENTIAL

Coffee grinding produces large quantities of static charge due to both fracturing and rubbing. Charge causes particle aggregation and discharge, a familiar problem in industrial coffee production. This study demonstrates that the magnitude of charge depends on the roast profile and, more importantly, the internal moisture content of whole-bean coffee. In an effort to control the charge, we demonstrate that the addition of external water mitigates its accumulation during grinding and promotes particle declumping. Notable differences in brew parameters are achieved. Implementation of our findings directly addresses a key issue of static accumulation and particle clumping and highlights the challenges of making physical property predictions based on bean color.

INTRODUCTION

Triboelectrification is the physical process where materials acquire surface charge from frictional interactions at their interfaces.[1] The magnitude of charge depends on the interfacial material composition[2] and can be harnessed in emergent technologies for energy generation.[3–7] The mechanism of electrostatic accumulation is complex and is further obscured in granular materials where collisions are sufficiently energetic to cause fracturing. In this "fractoelectric" regime, crack initiation and propagation are thought to charge particles through transfer of electrons and/or ions at the hot crack interface.[8,9] Whether a material's charging is dominated by tribo- or fractoelectrification, fracture-generated granular flows often comprise particles whose surface charge density may exceed the theoretical maximum value of 27 μC per meter squared[10–13] or charge-to-mass ratios in the range of 0.1–100 nC per gram.[14,15] There remains fundamental interest in studying the mechanism and magnitude of charging and methods to control the process, in particular to mitigate spurious effects such as electrostatic discharges and agglomeration within industrial settings.[16–20]

The electrification of chemically complex materials (e.g., foodstuffs, wood)[21] present unique and complex problems in materials science. While most food is not subject to fracturing resulting in appreciable electrical charge formation, coffee is a paragon of material complexity, as all coffee is ground, and the chemical composition of whole-bean coffee depends on numerous factors (e.g., roast, origin).[22–24] The effects are particularly emphasized in espresso preparation, where the coffee must be ground fine, imparting large amounts of static charge. Here, we use coffee to provide fundamental insights into the electrification processes in organic materials composed of a variety of molecules. We demonstrate that (1) conventional coffee parameters—roast, internal water content, grind setting—dictate the charging of roasted coffee and offer an explanation why, (2) both triboelectric and fractoelectric processes occur during grinding, with the majority of charging coming from fracturing events, and (3) charging depends on the coffee bean's internal and external water content, with higher water content suppressing charge accumulation. For industrial-scale operations, uncontrolled coffee charging can cause clumping, leading to product heterogeneities and clogged conduits. At the brewing level, aggregation may also affect liquid-solid accessibility,[25] leading to inhomogeneous extraction and unpredictably unpleasant espresso.[26] In the context of both understanding the fundamentals of triboelectrification and bolstering our efforts toward brewing more reproducible and sustainable coffee, this article offers strategies to control the charging of coffee particles and posits opportunities therefrom.

RESULTS AND DISCUSSION

Electrifying coffee

We first sourced numerous commercially roasted coffees, canvasing many major producing countries and coffee-processing paradigms. These coffees are further categorized by their processing method—natural (N), washed (W), and decaffeinated (D)—and are all single origin unless designated as a blend (B). Full details of the commercial coffees are presented in Table S1. The color of roasted coffee can be quantified using a spectrophotometric method that places coffee on the "Agtron gourmet scale."[27] The scale ranges from 0 (black/carbonized) to 150 (green/unroasted), with most specialty coffees falling within the range of 40–90 as measured on our spectrophotometer. Examples are presented in Figure 2.

To assess surface charging of whole beans, we first selected Starbucks Blonde Espresso Roast (a dark-roast coffee: Agtron 65.2, water content 1.3%) and rolled it down a vibrating ramp coated in various materials. At the end of the ramp, beans were collected in a Faraday cup, where the charge and weight were recorded (Figure 1A). Coffee generally charges poorly against metallic surfaces but may acquire relatively large charge when contacting dielectrics. To assess the charging of coffee against other materials, we created a series of heterointerfaces between whole-bean coffee and other common materials found in coffee-grinding environments. From Figure 1B, it is found that coffee charges positively against plastics such as polyvinyl chloride (PVC) and biaxially oriented polyethylene terephthalate (Mylar, a material widely used in coffee grinder technologies) but acquires negative charge when rubbed against glass and nylon (Figure 1B). Coffee gains almost no charge against office paper. These data indicate that coffee is similar to wood, cellulose, and grain in the triboelectric series.[2]

Coffee beans must be ground—a process that results in significant electrification. The process typically produces particles with sizes ranging from 100 nm to 2 mm. The distribution is controlled by grind setting and bean temperature.[28] In flat-burr grinder architectures such as the configuration housed within the Mahlkönig EK 43 (a grinder with steel 98 mm burrs; Figure 1C), the grind setting is determined by the separation between rotating metal plates. Finer grind settings result in more fracturing events, longer coffee-burr contact time, and the production of more fines

[1]Department of Earth Sciences, University of Oregon, 1272 University of Oregon, Eugene, OR 97403, USA

[2]Department of Chemistry, University of Oregon, 1275 University of Oregon, Eugene, OR 97403, USA

[3]Department of Physics, KAIST, Daejeon 34141, Republic of Korea

[4]Lead contact

*Correspondence:
jmendez7@uoregon.edu (J.M.H.),
chendon@uoregon.edu (C.H.H.)

https://doi.org/10.1016/j.matt.2023.11.005

Please cite this article in press as: Méndez Harper et al., Moisture-controlled triboelectrification during coffee grinding, Matter (2023), https://doi.org/10.1016/j.matt.2023.11.005

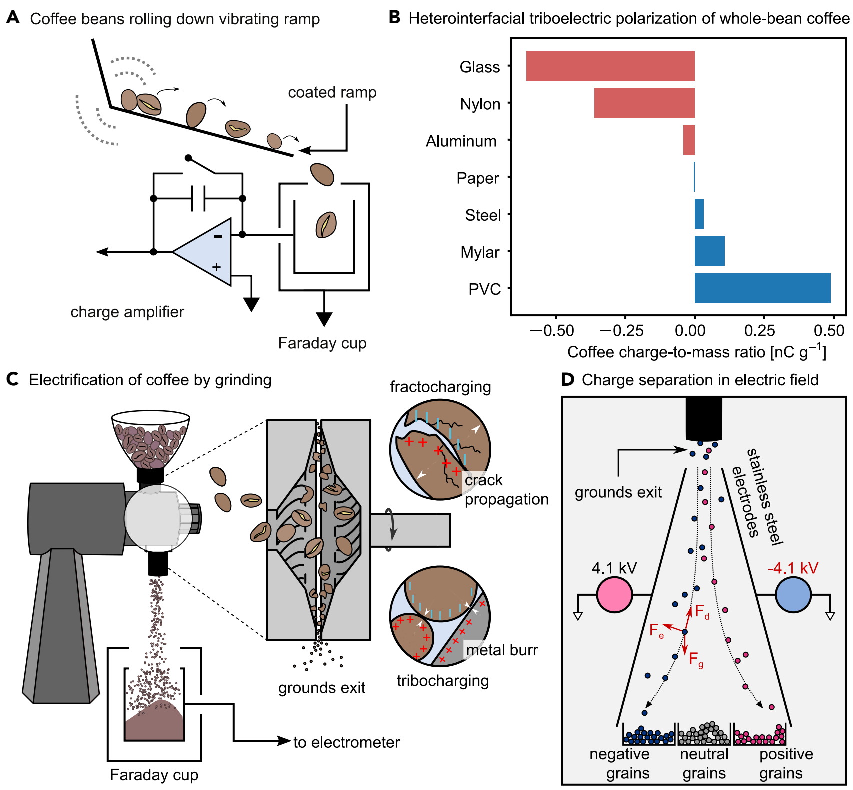


Figure 1. Electrification of coffee beans and particles

(A) Whole coffee beans accumulate charge when rolled down a vibrating ramp coated in a variety of materials.

(B) These surfaces materials can be arranged according to their capacity to charge whole beans. Here, Starbucks Blonde Espresso Roast weakly charges against steel, while glass and nylon result in positive charging, and plastics like PVC and Mylar lead to negative charging.

(C) During fracture, coffee particles accumulate charges from the burr-coffee interface and coffee-coffee rubbing (tribocharging), as well as fracture points (fractocharging).

(D) After grinding, the charge is quantified by alloying the particles to fall between two sub-parallel electrodes with a potential difference of 8.2 kV. The electric field separates particles by charge polarity, and particles are collected in negative, neutral, and positive bins at the base of the separator.

(sub-100 μm particulates) and smaller boulders (post-100 μm particulates). While grinding can lead to minute spark discharges, especially if the grinder is not grounded, the primary consequence of electrification is the formation of particle aggregates held together by electrostatic forces.

The net charge acquired by a coffee sample is measured by placing a Faraday cup under the grinder chute (Figure 1C). An electrometer then reports a voltage proportional to the particle charge with a sensitivity of 10 nC V^{-1}. Although we used 1 g (5–10 beans) coffee across all experiments, the amount of ground coffee that entered the Faraday cup varied between experiments (some material is retained in the space between the burrs). To account for this variation, we normalized the measured charge by the mass collected in the cup, allowing us to calculate a cumulative charge-to-mass (Q/m) ratio (i.e., the total charge of the coffee in the cup). Furthermore, we performed a different experiment to separate the positive, negative, and neutral particles. By replacing the Faraday cup with an electrostatic separator consisting of two sub-parallel plates held at a potential difference of ~ 8.2 kV

Please cite this article in press as: Méndez Harper et al., Moisture-controlled triboelectrification during coffee grinding, Matter (2023), https://doi.org/10.1016/j.matt.2023.11.005

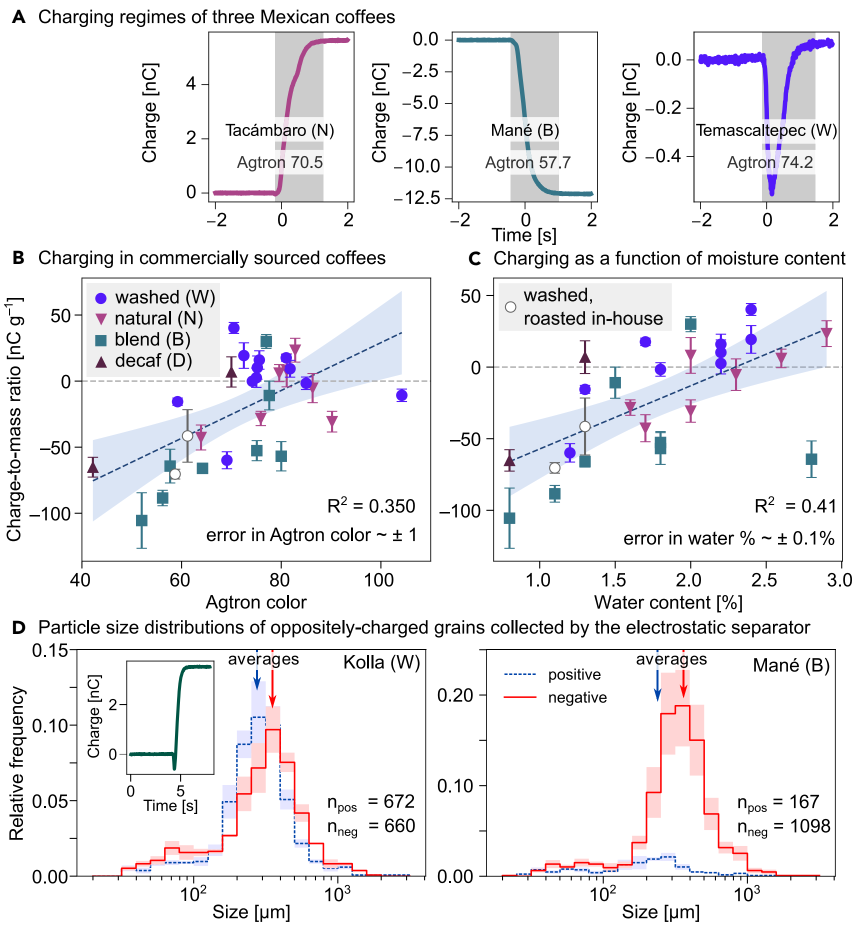


Figure 2. Charging regimes of commercially sourced coffees

(A) Three Mexican coffees—Tacámbaro (N), Mané (B), and Temascaltepec (W)—show three possible charging regimes.

(B) Charge-to-mass ratio as a function Agtron color for a variety of coffees ground at setting 2.0. There is no strong relationship between charge magnitude and polarity and coffee processing method. Confidence bands are plotted at 90%. A polarity switch is observed for darker coffees (Agtron $\leq$70). The magnitude of negative charge continues to increase with darkness.

(C) Internal moisture—a property proportional to roast color—results in more positive charging. Moisture content is a slightly better predictor of charge-to-mass ratio than color.

(D) Examination of the particles collected for two representative coffees, Kolla (W, a positive-charging coffee) and Mané (a negative-charging coffee), reveals that positively charged particles are generally smaller than the boulders, as denoted by the average arrows in blue.

Error bars in (B) and (C) indicate one standard deviation of a minimum of 3 measurements.

and grinding 10 g coffee, the negatively charged grains drift toward the positive plate and the positive grains toward the negative plate, and net neutral particles fall straight down (Figure 1D). Imaging and laser diffraction particle size analysis can then be used to determine whether polarity impacts size distributions, in addition to determining a Q/m for each bin.

General trends in electrification of grinding commercially roasted coffee

Using this experimental setup, we first examined three Mexican coffees (Figure 2A). Those samples showed net positive, net negative, and both positive and negative charging. But those coffees were roasted by different roasters to different colors, and the data suggest, perhaps unsurprisingly, that origin alone does not dictate the polarity of charge. Figure 2B summarizes the charging behavior of ~ 30 coffees as a function of Agtron color. Although we observed both positive and negative charging, the Q/m ratio magnitudes of positive samples are generally smaller ($< 50\ nC\ g^{-1}$) than that of negative coffees (up to120 $nC\ g^{-1}$). We observed a weak relationship between roast color and charging, with positive charging occurring only at Agtron values exceeding 70. Post-roast internal moisture content showed a slightly better relation to the sign and magnitude of charge (Figure 2C). Here, the transition from negative to positive charging occurs when the water content increases above ~2% by mass. The substantial scatter in Figures 2B and 2C likely reflect that Agrton color is not a unique property of any particular coffee—there are seemingly endless roast profiles that could be used to arrive at their color. For example, one could obtain a dark coffee by roasting at low temperature for a prolonged time or by roasting hot and fast. Additionally, the internal water content of pre-roast green coffee varies with time and depends on storage environment.[29] Both variables have a significant impact on roast chemical composition[30] and are also known to affect the resultant beverage properties.[31]

However, the relationship between water content in roasted coffee and charging transition from negative to positive is somewhat surprising given other reports of decreasing Q/m ratios with increasing moisture.[32] One possibility is that the polarity flip reflects degrees of strain at fracture.[33] In that work, lower degrees of strain were associated with negative charging. Because dark coffee is more brittle, they may support less strain before failure than their more ductile, light-roast counterparts.[34] Another possibility is that the water is affecting the physical properties of the coffee, which we will discuss later in this article.

Beyond performing net Q/m measurements, we also separated particles by polarity and then sized them photographically. An example particle size distribution of positive and negative coffees is presented in Figure 2D. These data suggest that the boulders carry a negative charge independent of roast, process, and origin. High-speed videography reveals that these boulders exit the grinder first, explaining why we occasionally observe negative charge entering the Faraday cup at the onset of grinding even if the net charge is ultimately positive (see inset in Figure 2D and the third panel in Figure 2A). Fine particles (<100 μm) tend to be biased slightly toward negative charging or have comparable positive and negative abundances. The distribution of charge on mid-size particles is more complicated. We observed a peak in the abundance of positively charged particles at diameters of 100–300 μm, regardless of net charge polarity. For light roasts, the abundance of particles in this size range exceeds that of negative grains. For coffees with lower Agtron values, the positive maximum is still present, but the quantity of negatively charged particles outnumbers positive particles at all sizes. In other words, the polarity of the particles in this intermediate range appears to dictate the overall polarity of a coffee's net Q/m ratio. This size range also corresponds to the sizes of particles typically produced for espresso format brewing, adding to the ever-increasing challenge of brewing reproducible espresso.[26]

Regardless of relative abundances, positive particles generally have smaller mean diameters than negative ones across all coffees (noted in Figure 2D by the average arrows). This size-dependent bipolar charging provides insight into the basic electrification mechanisms operating during grinding. The observation that the larger particles charge negatively is consistent with the charge separation described by James and co-workers[10] in the context of volcanic pumice fracture. Although equal numbers of positive and negative surfaces are likely created during any given fracture event, those authors hypothesize that subsequent ion-scavenging processes lead to particles of different sizes, concentrating opposite polarity charges. This bias—larger, negative particles and smaller, positive particles—is opposite to that often reported in purely triboelectric systems (i.e., processes with little to no fracture).[35] In those contexts, charge segregation has been attributed to the exchange of trapped electrons, polarization,[36] and hydrated ions.[37] For now, we can summarize that dark-roast coffees appear to charge more negatively than light roasts, that large particles carry negative charge, and that commercially roasted coffees charge in a seemingly unpredictable way.

Isolating the impact of roast profile

The data presented in Figure 2 point to a general challenge in the coffee industry: the words "light," "medium," and "dark" describe the end color and, to some extent, provide a touch point for flavor profile.[38] But roast color does not yield sufficient information about the chemical composition and resultant tribocharging. The large amount of scatter in the data likely reflects the compounded effects of origin and processing,[39] in addition to the temperature profile used to take it from green to brown.[40,41] Many commercial coffee roasters treat their roast profiles as proprietary, and it is impossible to back calculate the precise profile from examination of only the roasted whole beans. There is academic value in standardizing roast profiles across the industry, thereby allowing for direct comparisons between coffees. But we are not advocating for this on the industrial scale, as that would sterilize an artisanal aspect of the industry. Instead, we developed our own profiles with the aim of isolating roast through the development of systematically "darker" coffees.

Noting that pre-roast internal moisture content is known to dictate roast-induced swelling and other properties,[42] we sourced coffees with moisture content representative of conventional specialty coffees. We obtained a green Ethiopian coffee from the Yirgacheffe region, "YirgZ," featuring 12% internal moisture at the time of roasting. This coffee was roasted using an Ikawa Pro100 to achieve five different roasts by systematically increasing the terminal headspace air temperature and time by 2°C and 60 s, respectively (Figure 3A, blue). A sixth coffee was generated by adding 8°C and 180 s to the fifth profile. Additionally, a second roast profile was employed, differing by a parameter we call the "Morse time" (the empirical time taken for the headspace thermocouple to read a temperature equal to the initial temperature in an Ikawa roaster). The long Morse profiles were constructed in increments of 3°C and 60 s (Figure 3A, purple). Figure 3A shows the profiles for the shortest (solid) and longest (dotted) roasts. In summary, 12 dissimilar roasts were achieved; their details are presented in Table S2.

After degassing for 24 h, the coffees were ground at a setting of 2.0. Figure 3B shows the Q/m ratio of the YirgZ as a function of roast time for the two profiles. In both cases, the resultant charging is positive for short roasts (i.e., lighter coffees), with a transition to negative charging as the roast time increases. However, we observe an earlier transition to negative charging for the short Morse roast. To test whether these behaviors are specific to the YirgZ, we repeated the short roast experiment with a washed Mexican coffee, Yogondoy (9% internal moisture at time of roasting). The result of this ancillary experiment is presented in Figure 3B (gray squares). Within error, the Q/m ratios of the Ethiopian and Mexican coffees roasted using the same roast profile are comparable. Such congruence hints that the product of the roast, more than the characteristics of the green coffee, ultimately determines the charging behavior of coffee when ground.

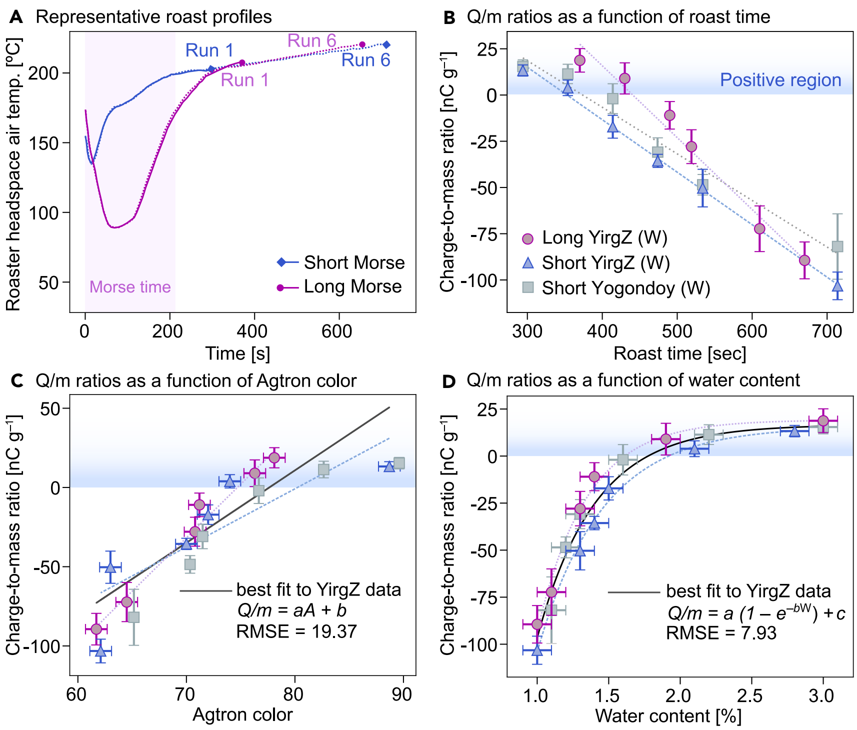


Figure 3. The effect of roast profile on charging

(A) Two sets of roast profiles were explored: short Morse (blue) and long Morse (purple).

(B) Charge-to-mass ratios as a function of roast time for a representative Ethiopian coffee (YirgZ) show that charging increases with darker roasts. Prolonged Morse transitions to the negative-charging regime at a slower rate than the shorter Morse. An additional Mexican coffee (Yogondoy) was roasted using the short Morse profile, yielding a similar electrification behavior to the Ethiopian coffee.

(C) Charge-to-mass ratios for Ethiopian and Mexican coffees as functions of Agtron color.

(D) Charge-to-mass ratios for Ethiopian and Mexican coffees as functions of residual water content. Error bars in (B), (C), and (D) indicate one standard deviation of a minimum of 3 measurements.

We can further test the hypothesis that roast is a primary control on charging by casting our data in terms of roast color and residual water content (Figures 3C and 3D, respectively). In agreement with the data presented in Figure 2, we observed weak linear relationship between color and electrification, with a transition from positive to negative charging at Agtron colors in the vicinity of 70–80. Lightly roasted coffee also retained more internal moisture than the darker roasted analogs (Figure 3D). In line with our findings in Figure 2C, we observe an abrupt transition to negative charging at water contents <2%. Notably, the internal moisture content appears to be a very good predictor for charging (root-mean-square error [RMSE] = 7.93 for charge versus moisture content compared to RMSE = 19.37 for charge versus Agtron). Also, dehydration follows an exponential relationship between moisture and charge, in line with the dehydration profile of bananas,[43] seeds,[44] and other foodstuffs. Together, these data suggest that internal water content is a primary factor in the electrification behavior of roasted coffee.

Grind-setting-dependent charging

Finer grind settings necessitate more fractures for the coffee to exit the grind chamber. Additionally, kinetic theory predicts that finer particle flows have higher granular temperatures (provided that particles have significant inertia to overcome fluid modification of granular temperature[45]), with individual grains undergoing large

Please cite this article in press as: Méndez Harper et al., Moisture-controlled triboelectrification during coffee grinding, Matter (2023), https://doi.org/10.1016/j.matt.2023.11.005

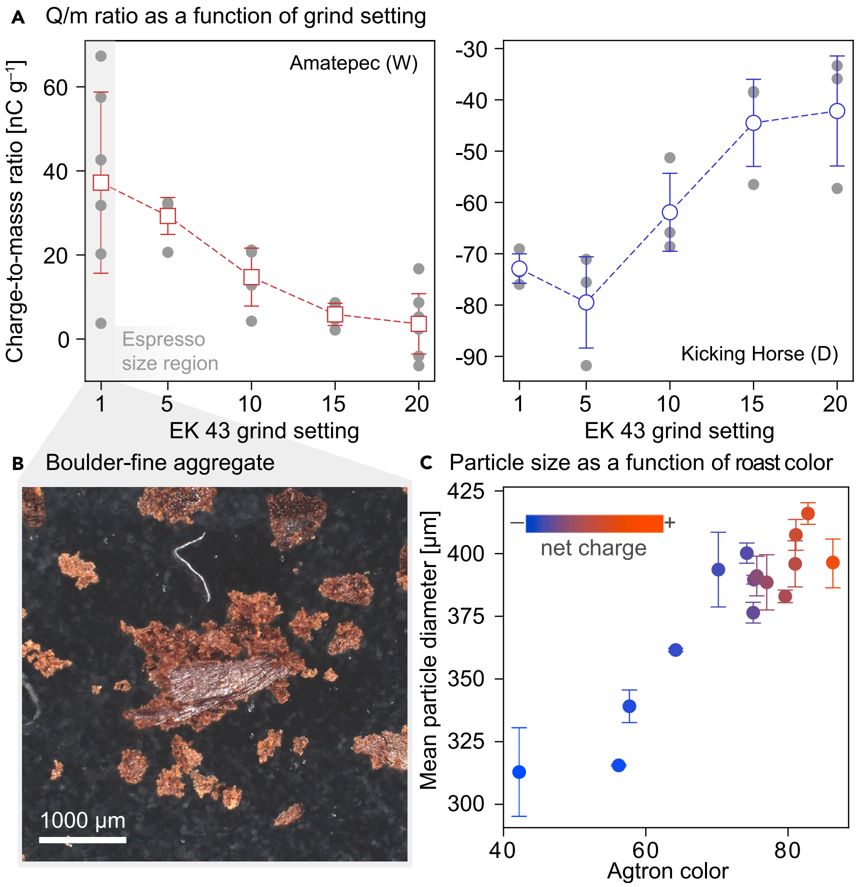


Figure 4. Charging as a function of grind setting and roast

(A and B) Charge-to-mass ratios of two representative coffees ground at settings spanning espresso (fine) to French press (coarse). In general, grinding finer increases charging, and at settings around 1.0 (the espresso region), positively charging coffees show a large spread in accumulated charge-to-mass ratio due to the formation of (B) aggregates as the coffee exists the grind chamber. For negatively charging coffees, grinding at 1.0 yields a slightly more positive average charge, with relatively small spread. We attribute this to the higher charging resulting in the very rapid formation of aggregates.

(C) At a constant grind setting, dark coffees have approximately 100 μm finer mean particle size than light coffees.

Error bars shown in (A) and (C) indicate one standard deviation of a minimum of 3 measurements.

numbers of collisions.[46] Thus, grinding finer should generate more charging through both fracto- and triboelectrification, regardless of polarity. To probe this hypothesis, we performed the same experiments presented in Figure 2 but at varied grind settings. Two examples are displayed in Figure 4A, revealing that coarser settings yield lower charge, independent of whether the coffee is positive charging (Amatepec, W) or negative charging (Kicking Horse, D).

The general trend is that the Q/m magnitude increases as coffee is ground finer. Yet some unexpected behavior is observed at the finest grind settings. For instance, Amatepec shows a large spread in the Q/m ratio values and microscopic examination reveals that the variance is attributed to the formation of aggregates, i.e., particles sticking to each other and other grinder surfaces (Figure 4B). The effect is exemplified in the Kicking Horse samples, where the finer particles have even higher surface charge and result in a minor reduction in observed electrification at the finest grind setting. We attribute this reduction to expeditious formation of the aggregates, analogous to those shown in Figure 4B.

Additionally, our measurements reveal that dark-roast coffees do produce much finer particles when ground at the same setting (Figure 4C). The darkest coffee in our dataset exhibits a −100 μm shift in particle size relative to the lightest coffee. These data build upon a previous study that showed that four light-roast coffees produced similar particle sizes[28] because they were similar in roast color. Figure 4C offers one explanation as to why darker coffees may yield slower espresso shots for the same brew parameters. It may not only be the increased volatile content[40] but also the reduced bed permeability.

Because finer grinding generates more charge, a direct relationship between roast and charge must include an empirical correction for the difference in particle sizes shown in Figure 4C. To do this, we can manually change the grind setting and monitor the particle size data until the dark- and light-roast coffees produce the same size distribution. In practice, this meant grinding dark roasts at a slightly coarser setting, 2.3, to achieve the same particle size distribution as our lightest coffee ground at 2.0. Figure S2 reveals that variations in particle size alone cannot account for the trends we observed in Figure 2. That is, dark-roast coffees accumulate more negative surface charge during grinding than their lighter relatives, independent of the size differences.

How granular mechanics influence electrification

With the impact of roast and grind isolated (where dark roasts and fine grinding yields the most charge), we next sought to investigate the impact of granular mechanics on electrification during coffee grinding. Much effort has been devoted to ascertain the roles of fragmentation and triboelectric charging in granular flows,[35,47,48] and some authors invoke a common physiochemical origin for charging.[49,50] Although this matter remains unsettled, it seems as though flows that do include material fracture behave differently from those that do not. For example, Lim and colleagues showed that pre-ground coffee particulates accumulated approximately −2 to −5 nC g^{-1} by simply rubbing upon a stainless-steel mixing auger and against themselves.[18] In contrast, coffees ground in our experiments gained absolute Q/m ratios exceeding 100 nC g^{-1}. This lays the foundation for the hypothesis that fragmentation processes are, to a large degree, responsible for electrostatic charging in coffee.

To isolate the impact of fracturing, we allowed ground coffee to pass through the grinder a second time at a coarser setting, preventing additional comminution. Without additional fracturing events, most charge should arise from coffee-coffee and coffee-burr interactions. The inset in Figure 5 shows the particle size distribution before and after the coffee traversed the grinder a second time, first at setting 2.0 and second at a much larger burr aperture (setting 6.0). The latter setting was selected because it was empirically shown to not alter the particle size distribution upon regrinding (see Figure S4 for further details). The minimal differences between the particle distributions indicate that pre-ground coffee particles are sufficiently small to exit the grind chamber without further fracture but still accumulate some charge. To assess the generality of this observation, we performed these experiments on seven coffees (Figure 5). Twice-ground coffees (black) acquired significantly less charge than their primary ground counterparts (gray). Indeed, we observe a reduction of charge by up to 90%, with most pre-ground coffees acquiring Q/m ratios in the range of 5–10 nC g^{-1}. Such values are comparable to the findings

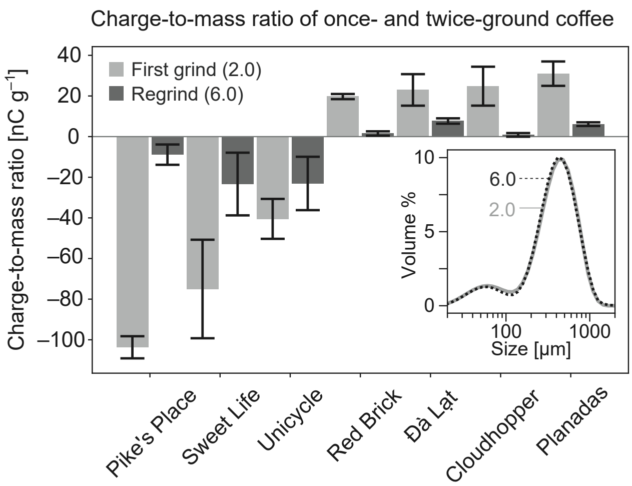


Figure 5. Twice grinding coffee to assess the role of fracture in electrification

The first grinding of whole-bean coffee at setting 2.0 results in charging from both triboelectric and fractoelectric processes, with a corresponding particle size distribution presented inset in gray. Regrinding the same particles at setting 6.0 results in a reduction in surface charge, with essentially no change in volumetric particle size distribution. First grinding is presented in gray and second grinding in black. Error bars indicate one standard deviation of a minimum of 3 measurements.

made by Lim and others[18] during the fluidization of powdered coffee. While we cannot isolate coffee-coffee and coffee-burr rubbing interactions, this experiment points to a general observation that reduced fracturing greatly reduces charging.

Grinding with supplemental external water and its impact on brewing

Recalling the progression toward zero/positive charging with increasing internal moisture (Figure 3D), we next sought to understand the impact of adding external moisture. This process—known in the coffee industry as the "Ross Droplet Technique"—was posited to have been originally presented on an online message board.[51–53] Anecdotally, baristas have observed that the incorporation of small amounts of liquid water onto the whole-bean coffee prior to grinding results in seemingly reduced charging. In our hands, it also resulted in near-zero grounds being retained by the grinder, an observation that has implications for reducing waste and increasing quality of beverages. Perhaps we will revisit this in a future study, but for now, we are more interested in whether the addition of water neutralizes the effects of fracto- and triboelectrification or modulates particle aggregation via capillary forces. Indeed, while abundant water does seem to preclude charge buildup,[54] recent work suggests that small amounts of free water during granular electrification can produce unexpected behaviors. For instance, Grosjean and Waitukaitis[55] showed that water can change the charging behavior randomly and irreversibly. Hu and colleagues found that the open-circuit voltage of a triboelectric nanogenerator increases with relative humidity up until values of 50%.[56] We also performed humidity experiments (Figure S4) and found that humidity only affected charging above approximately 60% relative humidity (RH), in line with Hu et al.[56]

To assess the impact of water addition, we systematically introduced water to whole-bean coffee and ground at setting 2.0. Q/m ratios as a function of added water are presented in Figure 6A. All commercially sourced coffees of varying darkness, moisture content, and origin/processing methods (see Table S1) show a systematic reduction in charging with increasing external water content. As water content approaches 20 μL g^{-1}, the charging approaches 0 nC g^{-1}. We performed further

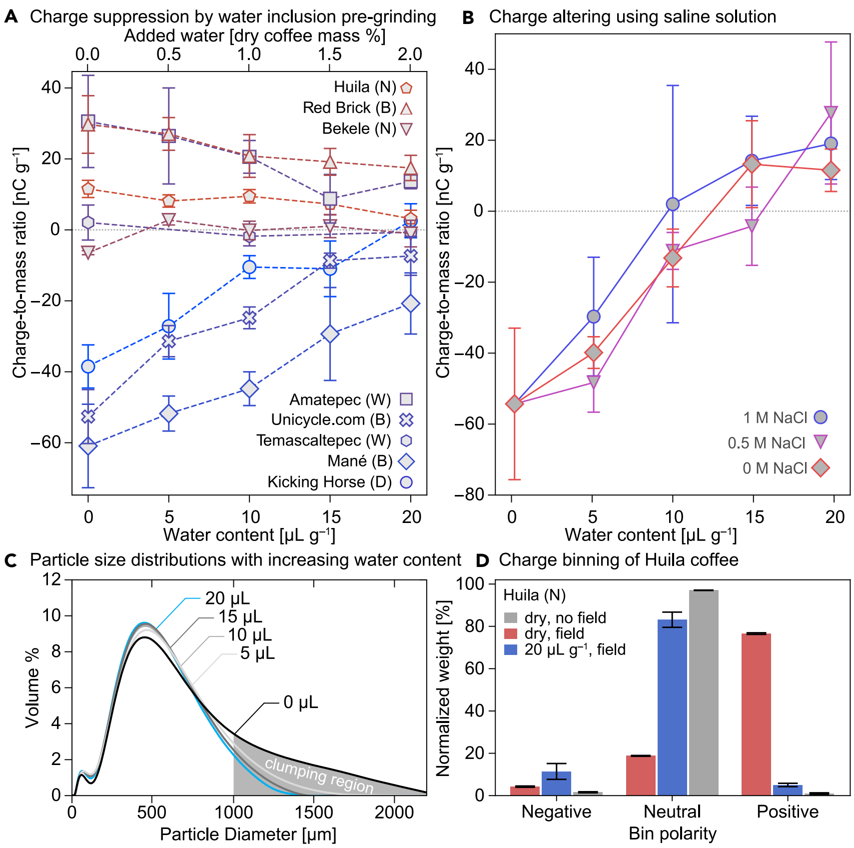


Figure 6. External moisture controls surface charging and causes particle deaggregation

(A) Charge-to-mass ratios for several coffees that span positive, neutral, and negative charging, with increasing amounts of water introduced to the whole beans prior to grinding. The red-to-blue coloring is indicative of the roast color, where blue represents darker roasts. The upper x axis provides an estimate for the effective change in total moisture content contained within, and coated on the surface of, the whole beans.

(B) The inclusion of minerals in the water solution has no effect on the magnitude of charge suppression achieved by the water itself.

(C) The inclusion of water during grinding causes deaggregation of fines from boulders.

(D) The redistribution of particle polarity upon the addition of 20 μL g^{-1} water added to the whole beans.

Error bars in (A), (B), and (D) indicate one standard deviation of a minimum of 3 measurements.

experiments to isolate the impact of ambient humidity and found that while humidity can begin to reduce charging above 60% RH (see Figure S4), all of our measurements were performed between 25% and 45% RH and were largely unaffected by atmospheric water. This result is somewhat surprising given the majority of charging comes from fractoelectrifying events and the water is only introduced to the surface of the whole beans near instantaneously prior to grinding (preventing uptake and homogeneous wetting of the insides of the coffee). Here, water may be acting to reduce interfacial temperatures during fracturing (the coffee does exit the chamber cooler in the presence of water; see Figure S5), or perhaps it is facilitating some other physical process, e.g., enabling rapid solvated ion transfer.

Because both tribo- and fractocharging may originate from electronic ionization, nuclear ion transfer, or a combination of the two,[57] we further developed an experiment to suppress ion transfer through the inclusion of ions directly into the wetting

Please cite this article in press as: Méndez Harper et al., Moisture-controlled triboelectrification during coffee grinding, Matter (2023), https://doi.org/10.1016/j.matt.2023.11.005

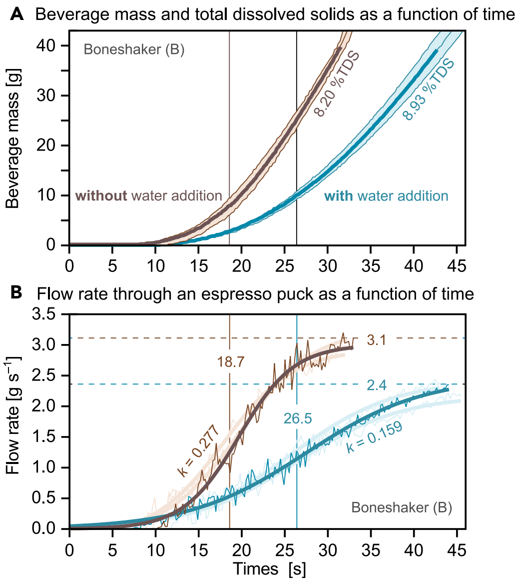


Figure 7. Shot-time and flow-rate dependence with and without water added to whole-bean coffee

(A) Without changing any other parameter, coffee prepared using the addition of water to whole beans during grinding produces consistently slower shots with increased beverage strength.

(B) The change in flow rate can be fit using a logistic function such that the permeability of the bed approaches a constant within conventional espresso brewing times. The time the sigmoid takes to reach its inflection is nearly half that of the shots prepared with coffee ground in the presence of water, indicating that the bed is more permeable and progresses toward equilibrium permeability more rapidly.

solution. If ion transfer is an operative mechanism, the inclusion of salt water should produce markedly reduced charging, dissimilar to that of pure water. Figure 6B reveals that the inclusion of NaCl, at either 0.5 or 1.0 M, shows the same fractoelectric charge reduction as that of pure water. These data lead us to conclude that ionic electrification is likely not the mechanism of charging in coffee but rather electron transfer.

To deduce whether the coffee particles were forming neutral aggregates, we examined both the laser diffraction particle size distributions as well as the electrostatic binning (Figures 6C and 6D). From the particle size distribution, it is clear that the inclusion of even small quantities of water (as low as 5 μL g^{-1}) results in an immediate reduction in electrostatic aggregates of boulders and fines (the clumping region in Figure 6C). From Figure 6D, the data reveal that a positive-charging coffee transitions to neutral, with a corresponding slight increase in negative particle formation. Taken together, we surmise that water directly passivates the fractoelectric and triboelectric charge formation in coffee and causes particle deaggregation. Thus, the water addition approach does appear to achieve two key goals in coffee grinding by reducing both positive and negative electronic charging and reducing clumping and should result in notable differences in flow dynamics when brewing.

The impact of the water addition during grinding was demonstrated by brewing some espresso. There, all espresso parameters were kept constant (18.0 g dry mass coffee was used to produce 45.0 g liquid coffee extract, ground at setting 1.0, tamped at 196 N, and brewed using 94°C water, kept at 7 bar static water pressure with a 2-s pre-infusion), and shot time and flow rate were hence dependent on the particle size and permeability of the espresso bed. From the data presented in Figure 7, several physical differences are noted. First, the shot time is nearly 50% longer for coffee produced using the addition of water. We understand this to be due to increased bed density; because the fines and boulders are not electrostatically attracted to one another, the average particle size is smaller. Second, despite this, the first drops of coffee make their way to the cup at approximately the same time (10 s). At the end of the shot, the espresso prepared without water added to the whole beans produces a cup concentration of 8.2% total dissolved solids

(TDSs), while the addition of water yields a cup with 8.9% TDSs. Perhaps the increase in concentration could simply be attributed to elongated contact time, but as we highlighted in an earlier paper,[26] shots with the same degree of extraction but different time parameters should have markedly different flavors.

Finally, we also examined flow rate throughout the shot. Because the coffee bed simultaneously swells while also being eroded, we hypothesized that the process should be described by a sigmoidal/logistic function where the flow rate will approach a constant as the espresso bed approaches a constant resistance (before the bed is either destroyed or channels are created). By fitting sigmoids to an average of three espresso shots for the wet- and dry-ground samples, we can calculate the rate at which the bed progresses to equilibrium flow. For the dry-ground samples, the rate is nearly 2× greater than the wet-ground analogs. This, paired with the mid-point of the sigmoidal fits, i.e., the time taken to reach the inflection point in flow rate, reveals that shots prepared without the addition of water during grinding are reaching equilibrium flow rates around the same time it takes the shot prepared with the addition of water to reach their inflection point. In other words, this is conclusive evidence to suggest that dry-ground coffee is producing a bed with markedly more porous pathways. By comparison to the exact same coffee but wet ground, we can conclude that wet grinding results in less space within the compacted bed and likely more homogeneous contact with water over the duration of the shot. Recalling that our previous study[26] highlighted that finer grind settings yielded uneven and variable extraction, here, we now offer one remedy to this variation. The addition of water during grinding should produce markedly different flavor profiles, and we expect that if one were to then alter both coffee mass and grind setting, the process should result in highly reproducible espresso.

What is the role of water in charge passivation?

It is clear that moisture controls charging. However, the precise basis for this observation remains enigmatic. One possibility is offered in a recent study by Shin and colleagues,[58] where the magnitude and polarity of electrification is predicted from an interfacial thermoelectric effect. In short, material charging can be predicted from their "triboelectric factor," a descriptor that relates a material's Seebeck coefficient (S) and the square root of the material's density (ρ), specific heat (c), and thermal conductivity (k) ($S/\sqrt{\rho c k}$). The sign of S is determined by the charge carrier type if they were to conduct electricity, i.e., positive for hole and negative for electron, and the magnitude of S depends on the electronic band gap (i.e., S of metals are nearly zero) and the location of the Fermi level. The Fermi level of most metals used in grinder burrs (e.g., steel with coatings of titanium nitride, diamond-like carbon) sit ca. -5.0 eV relative to vacuum.[59–61] Because the ρ and k values of metals are very high, the triboelectric factor of the burrs would be very small and positive. We note that other burr compositions will produce markedly different charging effects. For now, assuming the tribofactor of the burrs is treated as constant, we can then estimate how coffee parameters (roast, water content, grind setting) may affect the tribofactor of coffee particles by altering S, ρ, c, and k[62,63] and deduce qualitative trends in electrification.

Agtron number is proportional to the electronic band gap, both of which are reduced with darker roasts. This should cause the coffee's Seebeck coefficient to decrease with roast and, consequently, so should its tribofactor. This hypothesis generally aligns with the observation that oxidized organic molecules have low-laying unoccupied orbitals and explains the similarity in charging between coffee and other organic media.[2] Furthermore, because grinding causes heat (see

Figure S5), and assuming that the c and k are near unchanged for most coffees, but dark coffees generally result in smaller particles, darker coffees should heat up more and should produce increasingly negative charge. This concentration of negative charge on "warm," small particles has been previously invoked by Gu and co-workers to account for the fact that smaller, windblown sand particles are often observed to carry negative charge.[64]

The complicating factor then remains the role of residual internal water. One possibility is that water is affecting the internal pH, which in turn shifts the internal chemical potential or the Fermi level by 60 mV per pH unit.[65] At lower pH, the S should increase. However, the concept of pH is obscured in the coffee matrix, where the activities of protons are dissimilar to that of solvated acids. The concept is perhaps still instructive, as light-roast coffees generally contain more acid and moisture than dark-roast analogs.[66] The addition of external water may serve many purposes, including reducing thermal gradients during grinding, affecting the surface chemistry of the metal burrs, or facilitating recombination of nominally trapped charge carriers. Clearly, there are many unanswered fundamental questions, and we hope that this study provokes further work in the field.

Outlook and conclusion

From studying both commercially sourced and in-house roasted coffee, it is clear that many factors play a role in determining the magnitude of charging during grinding. Residual internal moisture content has a first-order effect, with lighter roasts (>2% internal moisture) showing positive charging. Drier coffees result in a transition to largely negative charging. The magnitude of polarity may then be modulated by the grind setting, with coarser grinds yielding less charging than finer grinds. There did not appear to be a dependence on origin or processing method. Instead, we can speculate that it is the interplay between color and moisture content that governs charging, and we highlight that after roasting, the color may not change much, but the internal moisture will depend on age, environment, and so forth. Perhaps this is why commercially sourced coffees behave less predictably than our sample roasts?

Furthermore, light, medium, and dark coffees and their roast profiles can feature markedly different charging regimes, even for coffees with the same Agtron values. This highlights that modern roasting paradigms are highly artisanal and pose fundamental challenges for using commercially sourced coffee in academic settings. This is important at both the small and large scales, potentially elevating quality control in roasting facilities. Similarly, one could imagine using the charging of whole-bean and ground coffee as a marker for a number of chemical and physical quality metrics. Could chemical defects be detected by monitoring the electrification of whole beans using the rolling technique presented in Figure 1?

We demonstrated that charging of coffee depends less on the initial water content of the green coffee and more so on the terminal water content (both internal and external) of the roasted beans. Through the inclusion of small amounts of external water, the coffee effectively declumps and suppresses charging during grinding. The same process provides tantalizing opportunities to introduce ions into the coffee grounds using salted water. One could imagine the development of in-ground mineralization to make designer brewing water[67] *in situ* without the risk of damaging boilers in espresso settings. To that end, we also demonstrated that the inclusion of water on whole-bean coffee results in markedly different flow dynamics in espresso brewing, which will undoubtedly yield differences in cup quality. The inspired reader is encouraged to experiment using the water addition technique but to further include both coffee mass (controlling the brew ratio and resultant strength) and grind setting (controlling flow restriction and resultant contact time) as variables. Wide implementation may reveal that a few simple squirts of water have solved the problems of clumping, channeling, and poor extractions while aiding in the pursuit of attaining the tastiest espresso.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

The lead contact for this paper is Christopher H. Hendon (chendon@uoregon.edu).

Materials availability

This study did not generate any new reagents.

Data and code availability

The data supporting this study is available for download from Figshare: https://doi.org/10.6084/m9.figshare.23277320.v2. Coffee roasting was performed using an Ikawa Pro100. The roast profiles are available for download.[68] The coffee color/roast degree and internal water content of both commercially sourced and in-house roasted coffee were measured using the Dipper KN-201 and the Roastrite RM-800, respectively. The Roastrite compensates for variations in ambient temperature and humidity.

Coffee grinding was performed on a Mahlkönig EK 43 flat-burr grinder using stock coffee burrs. The burrs were aligned using the Mahlkönig burr alignment tool. A grind setting of 0.0 was set when the burrs were brought together to create a chirping sound. The axial, radial, and angular alignments were measured by applying a marker to the outermost edges of the burrs and then bringing the burrs to grind setting 0.0. The burrs were sufficiently aligned where all radial markers had been rubbed away, and there was homogeneity of the grind distribution from laser diffraction particle size analysis. Laser measurements were performed on a Malvern Mastersizer 2000 with the solid-particle feed system Scirocco 2000. Vibration feed rate and air pressure were set to 60% and 2 bar, respectively. The standard operating procedure (SOP) parameters were three measurements per aliquot, a 2-s delay between measurements, an estimated refractive index and absorption of 1.59 and 0.1, respectively (similar to chocolate), a measurement time of 10 s, 10,000 measurement snaps, a background time of 5 s, and 5,000 background snaps. Raw data for plots presented in Figures 5 and 6 are available for download.[68] Twice-ground coffee in Figure 5 was obtained by first grinding at 2.0 and then at 6.0. These settings were empirically determined by isolating when the particle size distribution was unchanged during the second grind (see Figure S4 for further details). Grind settings less than 6.0 showed a minor increase in fines from random fracturing events of large particles. The raw triplicate data can be found online.[68] Photographic images were collected using a Keyence VHZ-100UR microscope.

Q/m quantification was performed using a custom-build Faraday cup, machined to fit the chute of the EK 43 grinder. The charge on particles entering the cup was then measured by a Keithley 614 electrometer operating in coulomb mode with a range setting of ± 2 nC (see Figure 1C). The coffee collected in the Faraday cup was then weighed using a generic laboratory scale to obtain its mass. The mass and charge were then used to compute the Q/m ratio. The same Faraday cup setup was employed to measure the triboelectric response of whole coffee beans rolling down a coated vibrating ramp presented in Figure 1A.

Particle charge polarity measurements were performed using the electrostatic separator following a configuration presented in a previous study.[35] The system shown in Figure 1C consists of two sub-parallel 1-m-long electrodes with a potential difference of 8.2 kV. The electric field separates particles by charge polarity, and particles were collected in negative, neutral, and positive bins at the base of the separator.

Water solutions used for fractoelectric charge reduction were constructed from reverse osmosis water from a Pentair Conserv 75E and mineralized using sodium chloride obtained from Sigma-Aldrich. A pipette was used to introduce water onto whole-bean coffee, and the coffee was shaken in a sealed container to ensure homogeneous distribution. Samples were prepared in triplicate.

Whole-bean coffee was stored in H_2O-impermeable vacuum bags and kept at −20°C. The coffee was allowed to equilibrate to room temperature in the vacuum bag before grinding. Humidity measurements were performed in a glovebox, and the grinder was allowed to reach equilibrium with the atmospheric water. Coffee was not allowed to equilibrate in order to isolate the role of internal versus external water. Otherwise, all experiments were conducted in air at 25°C ±2°C, 20%–45% RH, and 101 ± 1 kPa.

Espresso was prepared using a Victoria Arduino Black Eagle prepared at 7 bar static water pressure, with 94°C water and a fixed brew ratio of 18 g coffee to produce 45.0 g espresso. The grounds were tamped using PUQpress Q1, set to apply 196 N, and a normcore 58.5-mm diffusing screen was added to the top of the compacted bed. Flow-rate data were computed from the gravimetric change measured at the scale.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.matt.2023.11.005.

ACKNOWLEDGMENTS

The work was enabled by donations of green and roasted coffee from Square Mile, Tailored, Transcend, Onyx, Farmers Union, Passenger, Reverie, Stumptown, Sweet Bloom, Gracenote, Blueprint, Phil and Sebastian, Tim Wendelboe, Archetype, Colonna, Ona, Gorilla Gear, SuperJoy, Cà Phê, Proud Mary, Black & White, gget, George Howell, S&W Craft, Klatch, Monogram, Mother Tongue, Allegro, Keurig Dr. Pepper, Intelligensia, Counter Culture, Federico Barrueta, and Philip Andrango. We are grateful to Nuova Simonelli for providing the espresso machine and grinders, Ikawa for providing the roaster, Acaia for providing balances, PUQpress for providing a Q1 tamper, and Pentair for providing the reverse-osmosis water filtration system. We are grateful to Scott Rao for helpful discussions regarding ambiguities in describing roast profiles. J.M.H. and J.D. acknowledge support from DOE grant no. 242649 and NASA IDS grant 1911057Z4. C.H.H. acknowledges the support from the National Science Foundation under grant no. 2237345 and support from the Camille and Henry Dreyfus Foundation. This work was supported by the Coffee Science Foundation, underwritten by financial support for Nuova Simonelli. Y.-H.K. was supported by National Research Foundation of Korea (grant no. 2019R1A6A1A10073887)

AUTHOR CONTRIBUTIONS

The study was conceived by J.M.H., J.P., R.E.B., J.D., and C.H.H. Coffee was roasted by L.C.W. and J.M.H. Laser diffraction measurements were performed by E.J.R., C.S.M., R.E.B., L.E.L., and J.M.H. Triboelectric measurements were performed by J.M.H., L.E.L., and R.E.B. Espresso measurements were performed and interpreted by E.J.C. and C.H.H. J.M.H. and C.H.H. wrote the manuscript, and all authors contributed to the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: June 7, 2023
Revised: September 15, 2023
Accepted: November 3, 2023
Published: December 6, 2023

REFERENCES

1. Forward, K.M., Lacks, D.J., and Sankaran, R.M. (2009). Charge Segregation Depends on Particle Size in Triboelectrically Charged Granular Materials. Phys. Rev. Lett. *102*, 028001.
2. Zou, H., Zhang, Y., Guo, L., Wang, P., He, X., Dai, G., Zheng, H., Chen, C., Wang, A.C., Xu, C., et al. (2019). Quantifying the triboelectric series. Nat. Commun. *10*, 1427.
3. Li, M., Cheng, W.-Y., Li, Y.-C., Wu, H.-M., Wu, Y.-C., Lu, H.-W., Cheng, S.-L., Li, L., Chang, K.-C., Liu, H.-J., et al. (2021). Deformable, resilient, and mechanically-durable triboelectric nanogenerator based on recycled coffee waste for wearable power and self-powered smart sensors. Nano Energy *79*, 105405.
4. Zhang, R., and Olin, H. (2020). Material choices for triboelectric nanogenerators: A critical review. EcoMat *2*.
5. Luo, J., Gao, W., and Wang, Z.L. (2021). The Triboelectric Nanogenerator as an Innovative Technology toward Intelligent Sports. Adv. Mater. *33*, 2004178.
6. Cui, S., Zhou, L., Liu, D., Li, S., Liu, L., Chen, S., Zhao, Z., Yuan, W., Wang, Z.L., and Wang, J. (2022). Improving performance of triboelectric nanogenerators by dielectric enhancement effect. Matter *5*, 180–193.
7. Huo, Z.-Y., Yang, Y., Jeong, J.-M., Wang, X., Zhang, H., Wei, M., Dai, K., Xiong, P., and Kim, S.-W. (2023). Self-Powered Disinfection Using Triboelectric, Conductive Wires of Metal–Organic Frameworks. Nano Lett. *23*, 3090–3097.
8. Dickinson, J.T., Jensen, L.C., and Jahan-Latibari, A. (1984). Fracto-emission: The role of charge separation. J. Vac. Sci. Technol. A: Vacuum, Surfaces, and Films *2*, 1112–1116.
9. Wollbrandt, J., Linke, E., and Meyer, K. (1975). Emission of high energy electrons during mechanical treatment of alkali halides. Phys. Stat. Sol. *27*, K53–K55.
10. James, M.R., Lane, S.J., and Gilbert, J.S. (2000). Volcanic plume electrification: Experimental investigation of a fracture-charging mechanism. J. Geophys. Res. *105*, 16641–16649.
11. Méndez Harper, J., Dufek, J., and McAdams, J. (2015). The electrification of volcanic particles during the brittle fragmentation of the magma column. In In Proceedings of the ESA Annual Meeting on Electrostatics.
12. Méndez Harper, J., and Dufek, J. (2016). The effects of dynamics on the triboelectrification of volcanic ash. JGR. Atmospheres *121*, 8209–8228.
13. Méndez Harper, J., Dufek, J., and McDonald, G.D. (2021). Detection of spark discharges in an agitated mars dust simulant isolated from foreign surfaces. Icarus *357*, 114268.
14. Gibson, N. (1997). Static electricity—an industrial hazard under control? J. Electrost. *40–41*, 21–30.
15. Tanaka, Y., Miura, T., and Koyaguchi, T. (2002). Measurements of electric charge distribution in volcanic plumes at sakurajima volcano, japan. Bull. Volcanol. *64*, 75–93.
16. Hendrickson, G. (2006). Electrostatics and gas phase fluidized bed polymerization reactor wall sheeting. Chem. Eng. Sci. *61*, 1041–1064.
17. Salama, F., Sowinski, A., Atieh, K., and Mehrani, P. (2013). Investigation of electrostatic charge distribution within the reactor wall fouling and bulk regions of a gas–solid fluidized bed. J. Electrost. *71*, 21–27.
18. Lim, T.S.E., Lim, E., Tay, W.Q., Cruz, D.A., and Wong, S.Y. (2021). Triboelectric charging of 3-in-1 coffee mixes: Formulation and fouling. J. Food Process. Eng. *44*, e13890.
19. Matsusaka, S., Maruyama, H., Matsuyama, T., and Ghadiri, M. (2010). Triboelectric charging of powders: A review. Chem. Eng. Sci. *65*, 5781–5807.
20. Eckhoff, R.K. (2009). Understanding dust explosions. the role of powder science and technology. J. Loss Prev. Process. Ind. *22*, 105–116.
21. Zhang, L., Hou, J., and Bi, X. (2013). Triboelectric charging behavior of wood particles during pellet handling processes. J. Loss Prev. Process. Ind. *26*, 1328–1334.
22. Baffes, J., Lewin, B., and Varangis, P. (2005). Global Agricultural Trade and Developing Countries, *297* (World Bank Washington), p. 309.
23. Grigg, D. (2002). The worlds of tea and coffee: Patterns of consumption. Geojournal *57*, 283–294.
24. Cordoba, N., Fernandez-Alduenda, M., Moreno, F.L., and Ruiz, Y. (2020). Coffee extraction: A review of parameters and their influence on the physicochemical characteristics and flavour of coffee brews. Trends Food Sci. Technol. *96*, 45–60.
25. Gagné, J. (2021). The Physics of Filter Coffee (Scott Rao Coffee Books).
26. Cameron, M.I., Morisco, D., Hofstetter, D., Uman, E., Wilkinson, J., Kennedy, Z.C., Fontenot, S.A., Lee, W.T., Hendon, C.H., and Foster, J.M. (2020). Systematically Improving Espresso: Insights from Mathematical Modeling and Experiment. Matter *2*, 631–648.
27. Pires, F.D.C., Pereira, R.G.F.A., Baqueta, M.R., Valderrama, P., and Alves Da Rocha, R. (2021). Near-infrared spectroscopy and multivariate calibration as an alternative to the Agtron to predict roasting degrees in coffee beans and ground coffees. Food Chem. *365*, 130471.
28. Uman, E., Colonna-Dashwood, M., Colonna-Dashwood, L., Perger, M., Klatt, C., Leighton, S., Miller, B., Butler, K.T., Melot, B.C., Speirs, R.W., and Hendon, C.H. (2016). The effect of bean origin and temperature on grinding roasted coffee. Sci. Rep. *6*, 24483–24488.
29. Youn, K.-S., and Choi, Y.-H. (1990). Adsorption Characteristics and Moisture Content Prediction Model of Coffee with Water Activity and Temperature. Korean J. Food Sci. Technol. *22*, 690–695.
30. Gloess, A.N., Vietri, A., Wieland, F., Smrke, S., Schönbächler, B., López, J.A.S., Petrozzi, S., Bongers, S., Koziorowski, T., and Yeretzian, C.

(2014). Evidence of different flavour formation dynamics by roasting coffee from different origins: On-line analysis with PTR-ToF-MS. Int. J. Mass Spectrom. *365–366*, 324–337.

31. Telis-Romero, J., Gabas, A.L., Polizelli, M.A., and Telis, V.R.N. (2000). Temperature and water content influence on thermophysical properties of coffee extract. Int. J. Food Prop. *3*, 375–384.
32. Méndez Harper, J., Courtland, L., Dufek, J., and McAdams, J. (2020). Microphysical effects of water content and temperature on the triboelectrification of volcanic ash on long time scales. JGR. Atmospheres *125*, e2019JD031498.
33. Sow, M., Lacks, D.J., and Mohan Sankaran, R. (2012). Dependence of contact electrification on the magnitude of strain in polymeric materials. J. Appl. Phys. *112*, 084909.
34. Pittia, P., Dalla Rosa, M., and Lerici, C. (2001). Textural changes of coffee beans as affected by roasting conditions. LWT - Food Sci. Technol. *34*, 168–175.
35. Méndez Harper, J., Cimarelli, C., Cigala, V., Kueppers, U., and Dufek, J. (2021). Charge injection into the atmosphere by explosive volcanic eruptions through triboelectrification and fragmentation charging. Earth Planet Sci. Lett. *574*, 117162.
36. Pähtz, T., Herrmann, H.J., and Shinbrot, T. (2010). Why do particle clouds generate electric charges? Nat. Phys. *6*, 364–368.
37. Xie, L., Bao, N., Jiang, Y., and Zhou, J. (2016). Effect of humidity on contact electrification due to collision between spherical particles. AIP Adv. *6*, 035117.
38. Hu, G., Peng, X., Gao, Y., Huang, Y., Li, X., Su, H., and Qiu, M. (2020). Effect of roasting degree of coffee beans on sensory evaluation: Research from the perspective of major chemical ingredients. Food Chem. *331*, 127329.
39. Zarebska, M., Stanek, N., Barabosz, K., Jaszkiewicz, A., Kulesza, R., Matejuk, R., Andrzejewski, D., Biłos, Ł., and Porada, A. (2022). Comparison of chemical compounds and their influence on the taste of coffee depending on green beans storage conditions. Sci. Rep. *12*, 2674–2712.
40. Smrke, S., Wellinger, M., Suzuki, T., Balsiger, F., Opitz, S.E.W., and Yeretzian, C. (2018). Time-Resolved Gravimetric Method To Assess Degassing of Roasted Coffee. J. Agric. Food Chem. *66*, 5293–5300.
41. Arisseto, A.P., Vicente, E., Ueno, M.S., Tfouni, S.A.V., and Toledo, M.C.D.F. (2011). Furan Levels in Coffee As Influenced by Species, Roast Degree, and Brewing Procedures. J. Agric. Food Chem. *59*, 3118–3124.
42. Bustos-Vanegas, J.D., Corrêa, P.C., Martins, M.A., Baptestini, F.M., Campos, R.C., de Oliveira, G.H.H., and Nunes, E.H.M. (2018). Developing predictive models for determining physical properties of coffee beans during the roasting process. Ind. Crop. Prod. *112*, 839–845.
43. Dandamrongrak, R., Young, G., and Mason, R. (2002). Evaluation of various pre-treatments for the dehydration of banana and selection of suitable drying models. J. Food Eng. *55*, 139–146.
44. Ntuli, T.M., and Pammenter, N.W. (2009). Dehydration kinetics of embryonic axes from desiccation-sensitive seeds: An assessment of descriptive models. J. Integr. Plant Biol. *51*, 1002–1007.
45. Lattanzi, A.M., Tavanashad, V., Subramaniam, S., and Capecelatro, J. (2022). Fluid-mediated sources of granular temperature at finite reynolds numbers. J. Fluid Mech. *942*, A7.
46. Goldhirsch, I. (2008). Introduction to granular temperature. Powder Technol. *182*, 130–136.
47. Smith, C.M., Gaudin, D., Van Eaton, A.R., Behnke, S.A., Reader, S., Thomas, R.J., Edens, H., McNutt, S.R., and Cimarelli, C. (2021). Impulsive volcanic plumes generate volcanic lightning and vent discharges: A statistical analysis of sakurajima volcano in 2015. Geophys. Res. Lett. *48*, e2020GL092323.
48. Cimarelli, C., Behnke, S., Genareau, K., Harper, J.M., and Van Eaton, A.R. (2022). Volcanic electrification: recent advances and future perspectives. Bull. Volcanol. *84*, 78.
49. Piperno, S., Cohen, H., Bendikov, T., Lahav, M., and Lubomirsky, I. (2011). The absence of redox reactions for palladium (ii) and copper (ii) on electrostatically charged teflon: relevance to the concept of "cryptoelectrons". Angew. Chem. Int. Ed. *50*, 5654–5657.
50. Lacks, D.J., and Mohan Sankaran, R. (2011). Contact electrification of insulating materials. J. Phys. D Appl. Phys. *44*, 453001.
51. Moritz C. Ross droplet technique-eliminating grinder static. Home-Barista.com 2012. https://www.home-barista.com/grinders/ross-droplet-technique-eliminating-grinder-static-t24051.html.
52. Jana R. How to deal with static in coffee grinders: 3 tricks you can try at home. Java Presse 2021. https://www.javapresse.com/blogs/grinding-coffee/how-to-deal-with-static-in-coffee-grinders-3-tricks-you-can-try-at-home.
53. Clark, C. (2023). Ross droplet technique-eliminating grinder static. Brew Coffee at Home. https://www.brewcoffeehome.com/coffee-grinder-static-hack/.
54. Stern, S., Cimarelli, C., Gaudin, D., Scheu, B., and Dingwell, D. (2019). Electrification of experimental volcanic jets with varying water content and temperature. Geophys. Res. Lett. *46*, 11136–11145.
55. Grosjean, G., and Waitukaitis, S. (2023). Single-collision statistics reveal a global mechanism driven by sample history for contact electrification in granular media. Phys. Rev. Lett. *130*, 098202.
56. Hu, Y., Wang, X., Li, H., Li, H., and Li, Z. (2020). Effect of humidity on tribological properties and electrification performance of sliding-mode triboelectric nanogenerator. Nano Energy *71*, 104640.
57. Yang, P., Shi, Y., Tao, X., Liu, Z., Dong, X., Wang, Z.L., and Chen, X. (2023). Radical anion transfer during contact electrification and its compensation for charge loss in triboelectric nanogenerator. Matter *6*, 1295–1311.
58. Shin, E.-C., Ko, J.-H., Lyeo, H.-K., and Kim, Y.-H. (2022). Derivation of a governing rule in triboelectric charging and series from thermoelectricity. Phys. Rev. Res. *4*, 023131.
59. Tarditi, A., Kondratyuk, P., Wong, P.K., and Gellman, A.J. (2010). Controlling the work function of a diamond-like carbon surface by fluorination with XeF2. J. Vac. Sci. Technol. A: Vacuum, Surfaces, and Films *28*, 1250–1254.
60. Zhuang, Y., Liu, Y., Xia, H., Li, Y., Li, X., and Li, T. (2022). Effective work function of TiN films: Profound surface effect and controllable aging process. AIP Adv. *12*, 125222.
61. Gerard, A., Berry, A., and Masson, P. (2008). Optimization problem for the automatic positioning of flow obstructions to control tonal fan noise. J. Acoust. Soc. Am. *123*, 3539.
62. Cardoso, D.B., Andrade, E.T.d, Calderón, R.A.A., Rabelo, M.H.S., Dias, C.d.A., and Lemos, I.Á. (2018). Determination of thermal properties of coffee beans at different degrees of roasting. Coffee Sci. *13*, 498–509.
63. Pernstich, K.P., Rössner, B., and Batlogg, B. (2008). Field-effect-modulated Seebeck coefficient in organic semiconductors. Nat. Mater. *7*, 321–325.
64. Gu, Z., Wei, W., Su, J., and Yu, C.W. (2013). The role of water content in triboelectric charging of wind-blown sand. Sci. Rep. *3*, 1337.
65. Kim, Y.-H., Kim, K., and Zhang, S.B. (2012). First-principles calculation of thermodynamic stability of acids and bases under pH environment: A microscopic pH theory. J. Chem. Phys. *136*, 134112.
66. Duangjai, A., Saokaew, S., Goh, B.-H., and Phisalprapa, P. (2021). Shifting of physicochemical and biological characteristics of coffee roasting under ultrasound-assisted extraction. Front. Nutr. *8*, 724591.
67. Hendon, C.H., Colonna-Dashwood, L., and Colonna-Dashwood, M. (2014). The role of dissolved cations in coffee extraction. J. Agric. Food Chem. *62*, 4947–4950.
68. Méndez Harper, J., McDonald, C. S., Rheingold, E. J., Wehn, L. C., Bumbaugh, R. E., Cope, E. J., Lindberg, L. E., Pham, J., Kim, Y.-H., Dufek, J., et al.. Triboelectric coffee grinding supplemental raw data. FigShare. https://doi.org/10.6084/m9.figshare.23277320.v2.