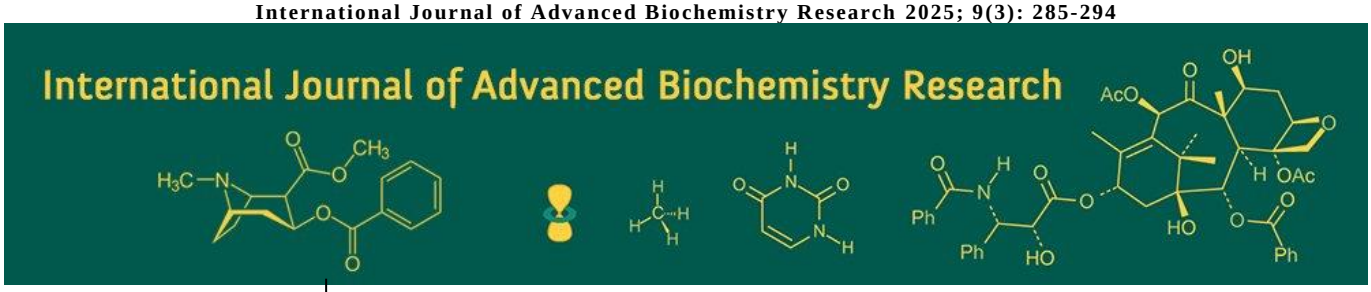

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Dr. Ramya M
Coffee Quality Division, Coffee Board, Bengaluru, Karnataka, India

Dr. Sandeep PM
Coffee Quality Division, Coffee Board, Bengaluru, Karnataka, India

Dr. Mandappa IM
Coffee Quality Division, Coffee Board, Bengaluru, Karnataka, India

Hari Om
Coffee Quality Division, Coffee Board, Bengaluru, Karnataka, India

Corresponding Author:
Dr. Ramya M
Coffee Quality Division, Coffee Board, Bengaluru, Karnataka, India

Exploring the effects of roast profiles and grind size on extraction dynamics and volatile fingerprinting in Indian coffee varieties

Ramya M, Sandeep PM, Mandappa IM and Hari Om

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Abstract
The extraction process is crucial for optimal coffee quality but remains understudied for various Indian coffee types. This study examines extraction dynamics in Indian Arabica Cherry, Indian Arabica Parchment, Indian Robusta Cherry, Indian Robusta Parchment, and Monsooned Malabar by varying roast profiles, grind sizes, and bean densities. Using a controlled pour-over method (coffee-to-water ratio of 1:17 at 92 °C), we measured Total Dissolved Solids (TDS) and extraction yield across light, medium, and dark roasts and coarse, medium, and fine grinds. Light and medium roasts yielded moderate extraction percentages (19-21%), while dark roasts showed a broader range (17.8% to over 23%). Monsooned Malabar's unique processing led to distinct extraction behavior due to altered bulk density and moisture content. Statistical analysis confirmed significant effects of roast profile and grind size on extraction efficiency, affecting TDS levels and overall yield. Volatile compounds were characterized using an electronic nose (e-nose) system, with heat maps showing distinct extraction patterns and bar charts illustrating volatile profiles.

Keywords: Extraction dynamics, Indian coffee, roast profiles, grind size, TDS, Monsooned Malabar

Introduction
Coffee is one of the most widely consumed beverages globally, and its quality is largely determined by the efficiency and dynamics of the extraction process [1]. Extraction, a complex solid-liquid operation, governs the dissolution of key chemical compounds that contribute to the beverage's flavor, aroma, and body [2]. Despite significant advances in understanding coffee chemistry, the influence of processing variables on extraction kinetics remains inadequately explored, particularly for Indian coffee varieties.

The extraction efficiency of coffee is affected by several critical factors. Roast profiles alter the chemical makeup and physical structure of the beans, thereby influencing the ease with which soluble compounds are released during brewing [3]. Grind size, by controlling the surface area available for mass transfer, plays a pivotal role in modulating extraction rates. Furthermore, bean density, which changes with roasting, affects the porosity and water flow through the coffee bed [4]. Together, these parameters determine the Total Dissolved Solids (TDS) [5-8] and extraction yield, which are central to achieving a balanced and high-quality cup. Roasting significantly alters the chemical composition of coffee. The Maillard reaction, caramelization, and other heat-induced chemical reactions during roasting lead to the formation of various volatile and non-volatile compounds [9].

Different coffee varieties exhibit distinct extraction behaviors due to their inherent structural differences. Arabica beans, known for their sweeter and more aromatic profile, typically have a finer texture and a more pronounced chemical composition, which affects the extraction dynamics. In contrast, Robusta beans, which have a higher caffeine content and a more bitter profile, require different extraction conditions to optimize flavor and body [4]. Although previous studies have addressed general extraction behavior in coffee [1, 7, 10, 11], much of this work has been focused on international varieties and conventional brewing methods, with limited attention given to the unique characteristics of Indian coffee, especially the diverse processing methods (e.g., Monsooned Malabar).

Previous research has predominantly focused on conventional brewing methods such as espresso [12-15] and filter coffee [16, 17].

Petracco [2] highlighted the importance of optimizing extraction to balance the diverse chemical constituents in coffee, while Illy and Viani [4] demonstrated the relationship between brew ratios, TDS, and extraction yield using brewing control charts. However, studies addressing the extraction dynamics of diverse Indian coffee varieties—including Arabica, Robusta, Washed, Unwashed, and the uniquely processed Monsooned Malabar—are sparse.

In this study, we address this gap by systematically investigating how variations in roast profiles (light, medium, and dark), grind sizes (coarse, medium, and fine), and bean densities affect the extraction dynamics in these Indian coffee varieties. Employing a controlled pour-over brewing method, we aim to quantify the impact of these variables on TDS and extraction yield, thereby proposing optimized brewing parameters for enhanced extraction efficiency and consistent coffee quality.

Materials and Methods

Coffee Samples and Experimental Location: Green coffee beans representing diverse Indian varieties—Arabica, Robusta, Washed, Unwashed, Monsooned Malabar—were procured from established estates across India. All samples were stored under controlled conditions until analysis. The experiments were conducted at the Sensory and Roasting Laboratory of the Coffee Board, Bengaluru, India. The initial moisture content of both green and roasted beans was determined with a SINAR AP 6070 Moisture Analyzer and was as per the standards between 11 to 12%.

Roasting Procedure: Green coffee samples were roasted using a bullet roaster (Aillio Bullet R1), ideal for small-batch operations. Three distinct roast levels were produced: light, medium, and dark. Each batch (approximately 100 g) was roasted under standardized conditions, and the degree of roast was verified using an Agtron colorimeter. Typically, according to the SCA, light roasts are roasted to achieve Agtron value in the 65-75 range, medium roasts around 55-65, and dark roasts in the 45-55 range. After roasting, the beans were promptly cooled to room temperature to arrest further chemical reactions.

Bulk Density Measurement: Bulk density, an indicator of bean porosity and structural integrity, was measured for both green and roasted samples. Beans were gently poured into a 100 mL plastic cylinder without compaction, and the mass required to fill the cylinder was recorded. Bulk density (g/cc) was calculated as:

Bulk Density = Mass (g) / Volume (cc)

Grinding and Particle Size Analysis: Post-roasting, beans were ground using a commercial grinder to achieve three distinct grind sizes: Fine, Medium and Coarse. Particle size distribution was confirmed using a laser diffraction particle size analyzer (Horiba Partica LA-960V2) to ensure consistency, as grind size directly influences the surface area available for extraction.

Brewing Procedure: A standardized pour-over method using a V60 dripper was employed to isolate extraction dynamics. For each brew, 15 g of ground coffee was used at a fixed coffee-to-water ratio of 1:17. Water was heated to 92 °C. The brewing process began with a 60 mL water pour for a 30-second bloom phase, followed by staged additions to reach a final volume of 315 mL. The complete extraction process lasted 3 minutes.

Determination of TDS and Extraction Yield: The Total Dissolved Solids (TDS) of each brewed coffee sample were measured using a calibrated refractometer (Atago Refractometer RX-7000i). Extraction yield (EY) was calculated using the formula:

EY (%) = (Brewed Coffee Weight (g) × TDS (%)) / Coffee Dose (g)

This calculation method follows guidelines provided by the Specialty Coffee Association

Electronic Nose Volatile Analysis: Volatile organic compounds (VOCs) were analyzed using an electronic nose system. Prior to sample analysis, the sensor array was calibrated with known volatile standards. The Alpha MOS Heracles Neo E-nose (Model: Heracles Neo 300, Manufacturer: Alpha MOS, France) was used to identify the aromatic components in the mango samples. The aroma compounds of R&G Coffee Blends were analyzed using dual-flash gas chromatography combined with electronic nose technology. In this method, a sealed vial or container allows low-boiling compounds to migrate between the sample and the headspace layer. The R&G coffee blends was weighed (2 g) into 20 mL glass vials. The vials, which were sealed with 20 mm steel crimp caps (PTFE/silicone septa-8 mm center hole), were incubated at 60 °C for 20 min with an agitation speed of 500 rpm. Next, the robotic arm transferred the vials from the sample tray to the auto sampler agitator. During the incubation process, odor components gradually evaporated and concentrated in the gas phase of the headspace until reaches equilibrium. Subsequently, the gas was injected into the injector and concentrated in a cold trap. After flushing, the trap was heated, and the concentrated odor was swiftly injected and split between the MXT-5 (10 m × 0.18 mm × 0.4 μm) and MXT-1701 (10 m × 0.18 mm × 0.4 μm) columns during the injection phase.

The sample analysis parameters were set as follows: an injection volume of 5000 μL at a rate of 125 μL/s, which was performed at a temperature of 200 °C with a 45 s injection period. Trapping occurred at 50 °C for 50 s with a split of 10 mL/min. The oven temperature program was as follows: starting at 50 °C for 2 s, ramping at 1.0 °C /s to 80 °C for 0 s, and then ramping at 3 °C/s to 250 °C for 21 s. The FID detector was maintained at a temperature of 260 °C. Hydrogen was used as the carrier gas at a flow rate of 1 mL/min.

For qualitative and quantitative analysis of the volatile components in the sample, 20 μL of headspace calibration mixture ranging from C6 to C16 was transferred into vials, and the incubation and analysis conditions were set to those of the samples. Subsequently, qualitative analysis was performed in the ArochemBase database based on the double-column relative retention index of each peak.

Data Analysis: Statistical analysis

The assays were designed and performed in three replicates and expressed in a statistical approach considering the standard error (SE) and standard deviation (SD) for the

mean values. Microsoft Excel program (Microsoft Corporation, USA) was used for all statistical computations. The experimental data—including TDS, extraction yield, and electronic nose volatile responses—were statistically analyzed using analysis of variance (ANOVA) to assess the effects of roast level, grind size, and coffee variety. Multivariate analysis was also employed to explore correlations between physicochemical extraction parameters and volatile compound profiles. A significance level of $p<0.05$ was set for all tests. This comprehensive approach enabled a detailed evaluation of how individual and interactive factors influence extraction dynamics in Indian coffee varieties.

Results and Discussion

The density analysis reveals clear patterns between varieties, processing methods, and roast levels. The data shows (Fig.1) Robusta beans maintain higher densities through roasting while Arabica varieties show more dramatic density changes. Processing methods (parchment vs cherry) significantly impact density behavior during roasting. The monsoon processing of Malabar Arabica results in the most stable density across roast levels, suggesting the pre-processing affects the bean's structural response to roasting. The changes in bulk density highlight significant differences in how each variety responds to roasting. Arabica beans (both Cherry and Parchment) generally exhibit more drastic changes in density with increased roast levels than the Robusta. The analysis provides a quantitative basis to further explore how these density changes might influence brewing parameters or product quality. On average, Dark roasts result in the greatest density loss (around-47.21%), followed by medium roasts (approximately-43.26%), and Light roasts show the least loss (about-37.47%). Illy and Viani [4], have also demonstrated that roasting affects the physical properties of the coffee bean, such as bulk density, which in turn influences extraction behavior

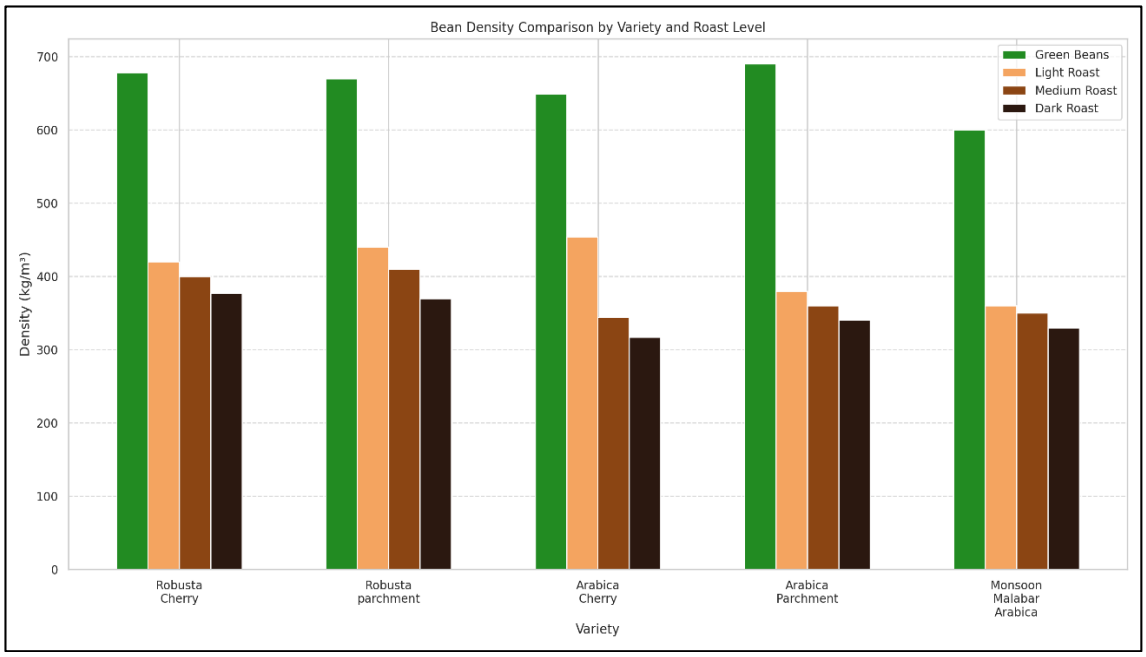

Fig 1: Comparison of Bean Density by Variety and Roast level

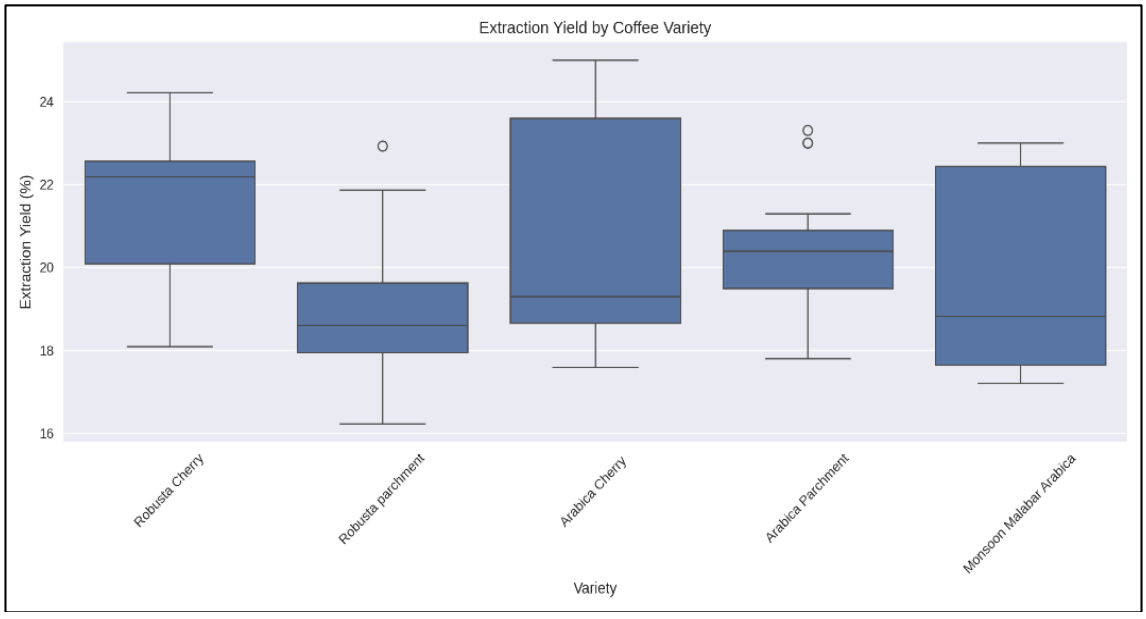

Fig 2: Impact of Variety of Coffee on Extraction Yield

The coffee variety plays a significant role ($F \approx 136.08$, p<1e-37). The boxplots (Figure 2) indicate that different varieties (e.g., Arabica versus Robusta) lead to distinct extraction profiles

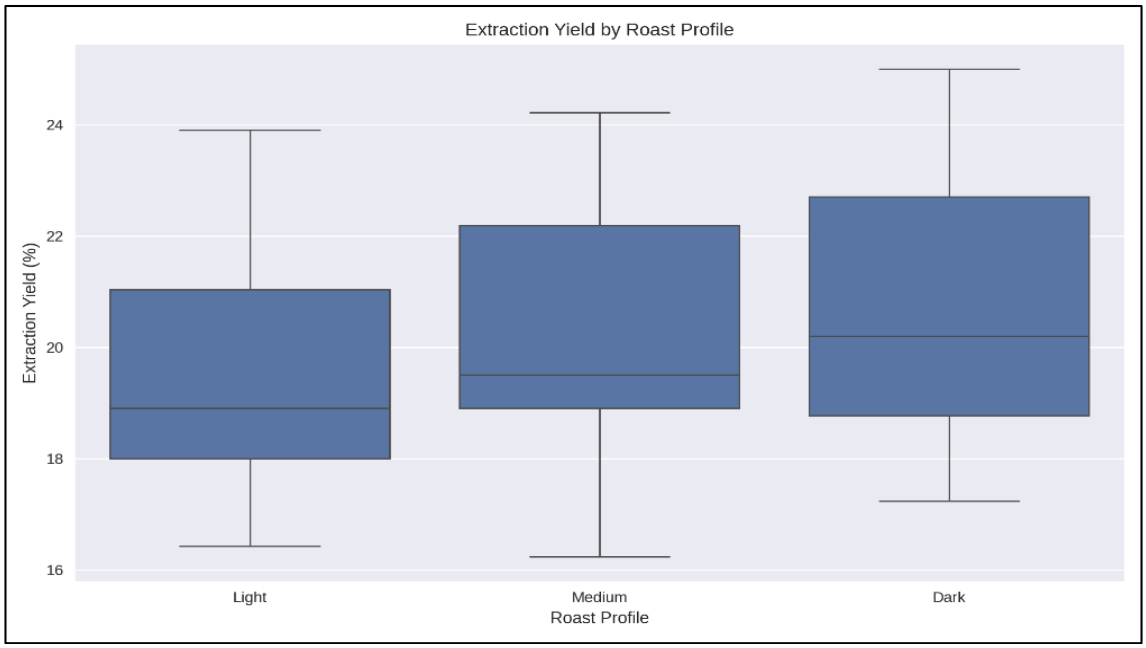

Fig 3: Impact of Roast Profile of Coffee on Extraction Yield

Although its main effect is the smallest among the three ($F \approx 78.64$, p<1e-20), roast profile still significantly affects extraction. For example, dark roasts generally yield higher extraction than light roasts (Fig.3). The relationship between roast level and volatile compound development has been explored in several studies. Lingle (2011) demonstrated that dark roasts tend to emphasize more caramelized and bitter flavors, while light roasts preserve fruity and floral notes. This is due to the progressive breakdown of sugars and the formation of Maillard reaction products and caramelized sugars in darker roasts.

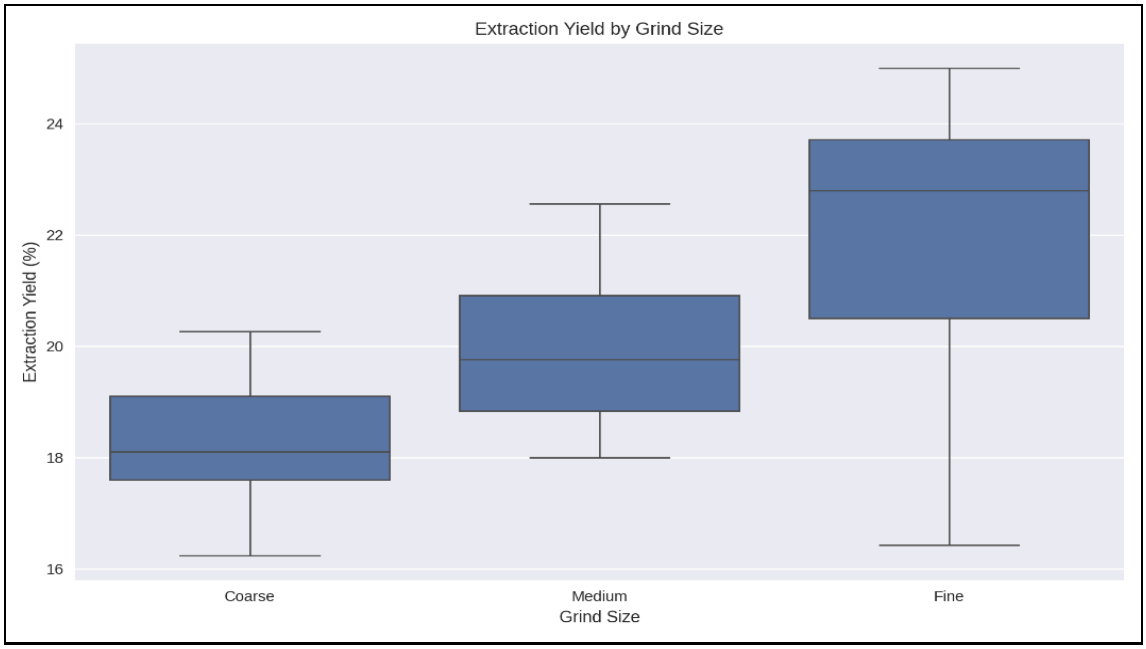

Fig 4: Impact of Grind size on Extraction yield

This factor shows the largest effect with an extremely high F-value in the ANOVA ($F \approx 923.60$, p<1e-60). Across the data, fine grinds produce a much higher extraction yield compared to medium and coarse grinds. A study by Illy and Viani [4] demonstrated that fine grinds produced higher Total Dissolved Solids (TDS), contributing to a stronger and more intense coffee. However, overly fine grinds can lead to over-extraction, resulting in bitter flavors, a challenge that roasters and brewers must balance.

The effect of grind size on extraction yield has been corroborated by research in which fine grinds consistently resulted in higher extraction yields than coarse grinds, particularly in dark roasts [3]. The current study aligns with these findings, where fine grinds were shown to enhance extraction yields, particularly in Robusta and Arabica varieties.

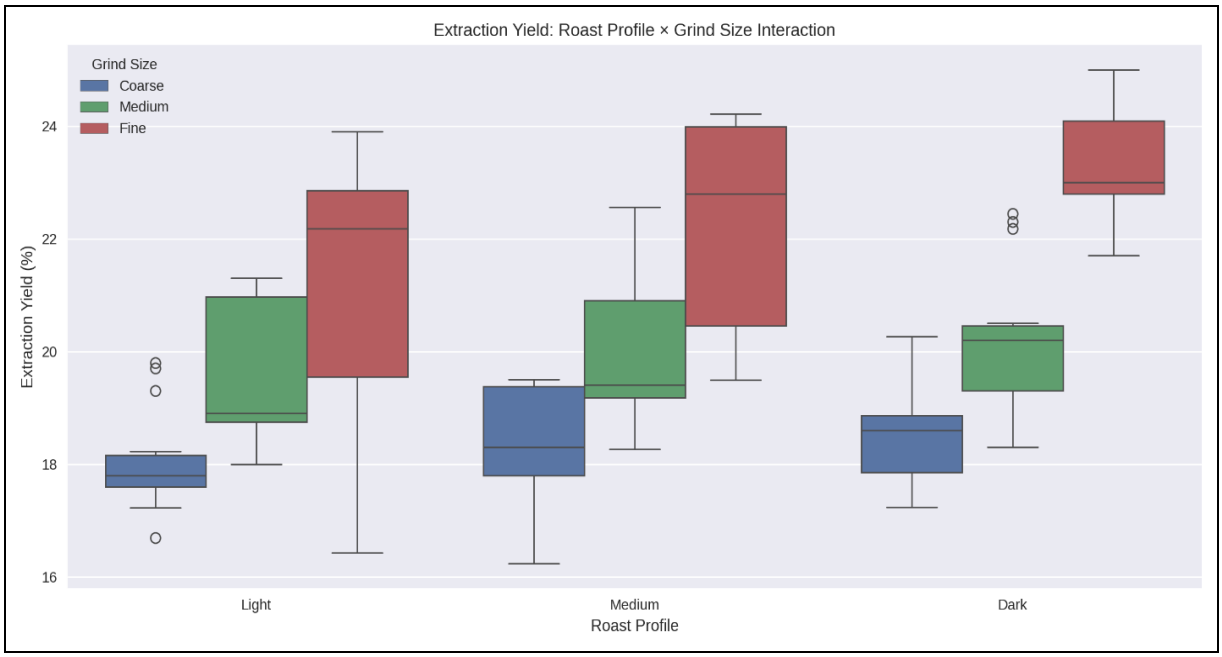

Fig 5: Impact of Roast profile and Grind size on Coffee Extraction

The two-way ANOVA (including all interactions) reveals that the interplay between roast profile, and grind size is highly significant, implying that the optimal extraction behavior does not depend on a single parameter but rather on their combination.

The interaction plot (Fig. 5) shows that while the effect of grind size is consistent (fine always yielding more extraction), the magnitude of differences across roast profiles can vary with the grind size chosen. This means that while fine grinds lead to higher extraction regardless of roast, the specific yield changes when considering roast profile.

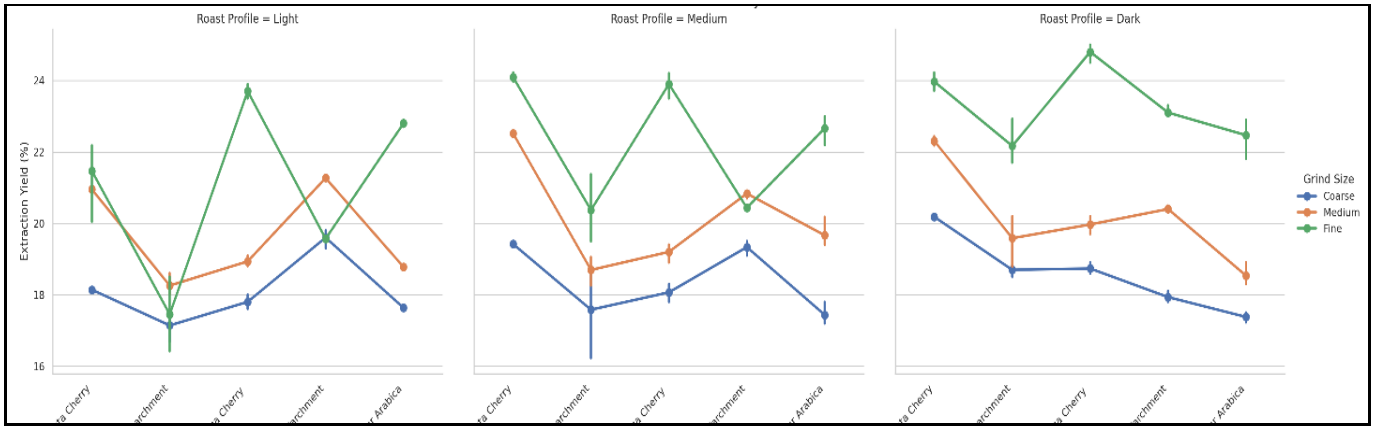

Fig 6: Impact of Variety, Roast profile and Grind size on Coffee Extraction

Fig.6 (the point plot with 95% confidence intervals) provides a clear summary of the mean extraction yields across different varieties, grouped within each roast profile. When optimizing coffee extraction, it is not enough to adjust one variable (say, grind size) in isolation. Instead, one must consider how the bean variety and roast profile interact with the chosen grind size. The impact of roast profile varies depending on both variety and grind size insisting that the optimal extraction behavior does not depend on a single parameter but rather on their combination.

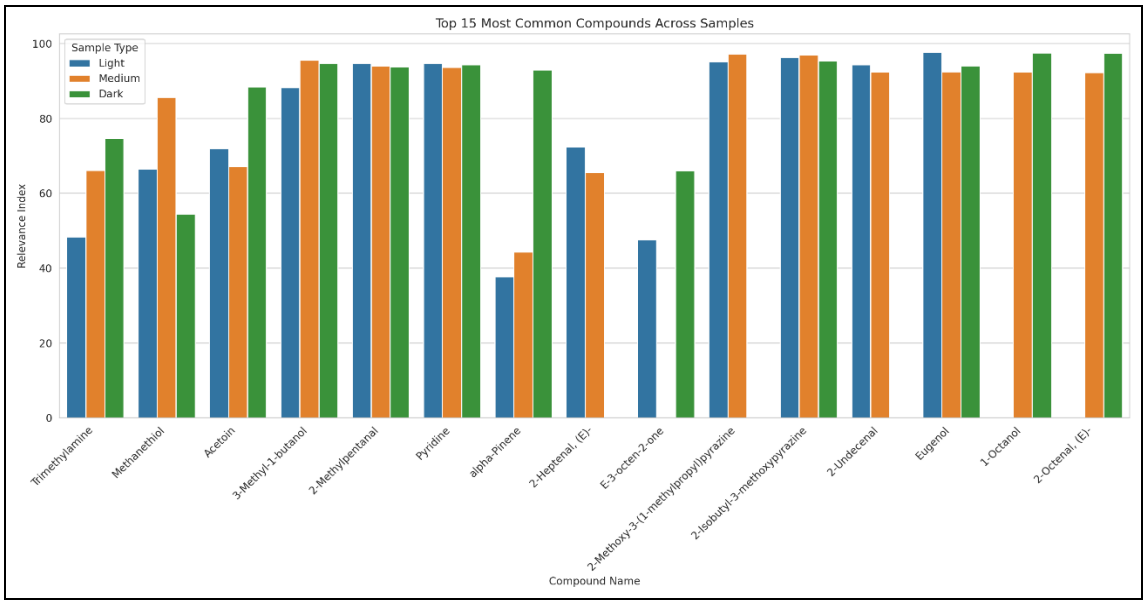

Fig 7: Common Volatile Chemical compounds across different Roast profiles of Indian Arabica Parchment

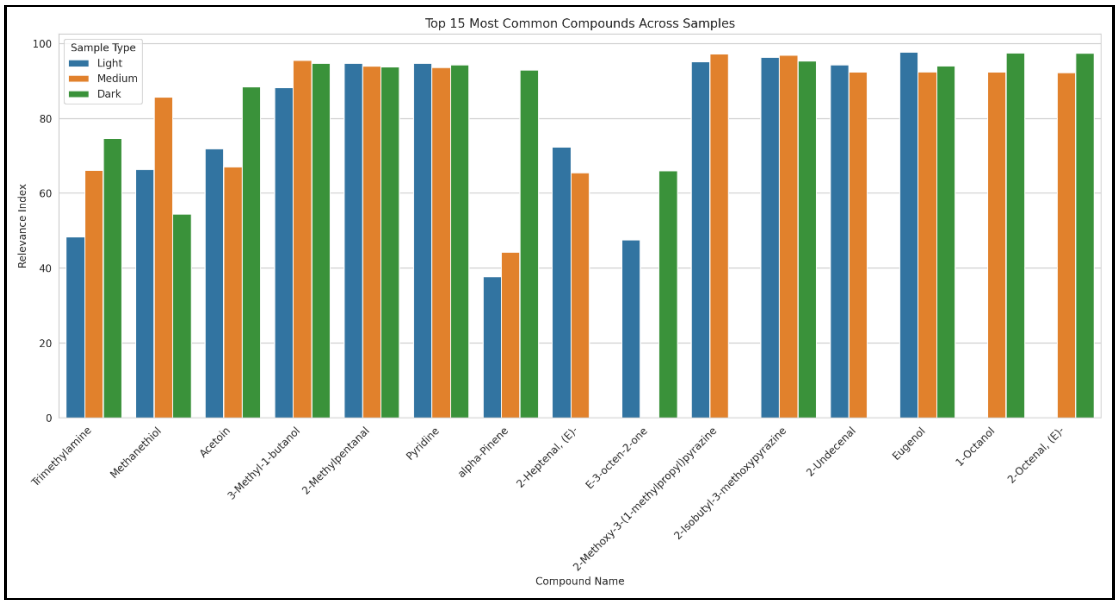

Fig 8: Common Volatile Chemical compounds across different Roast profiles of Indian Arabica Cherry

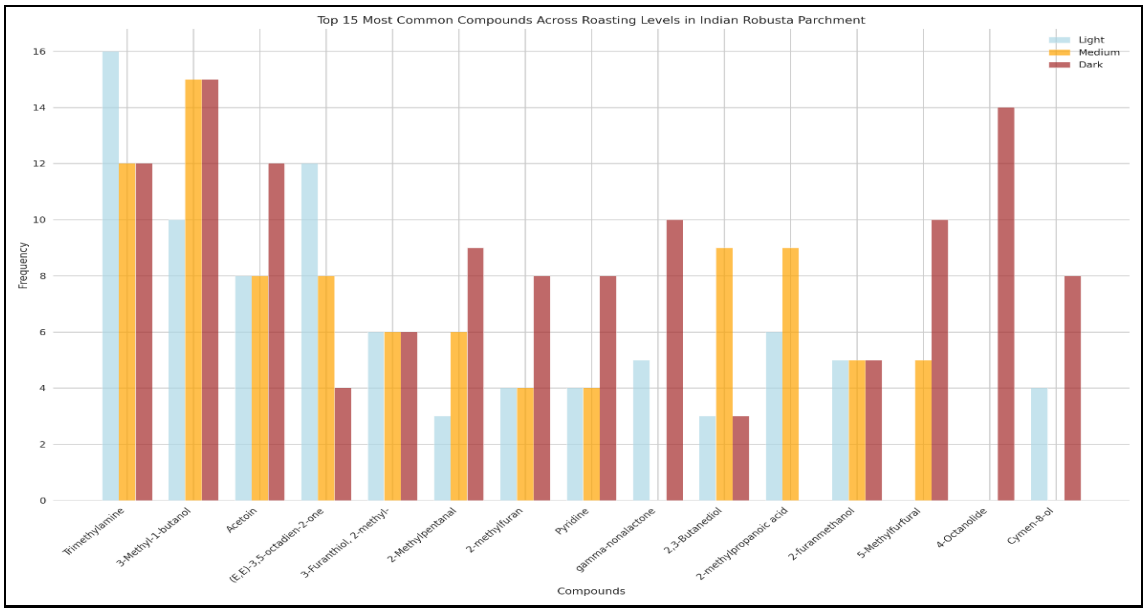

Fig 9: Common Volatile Chemical compounds across different Roast profiles of Indian Robusta Parchment

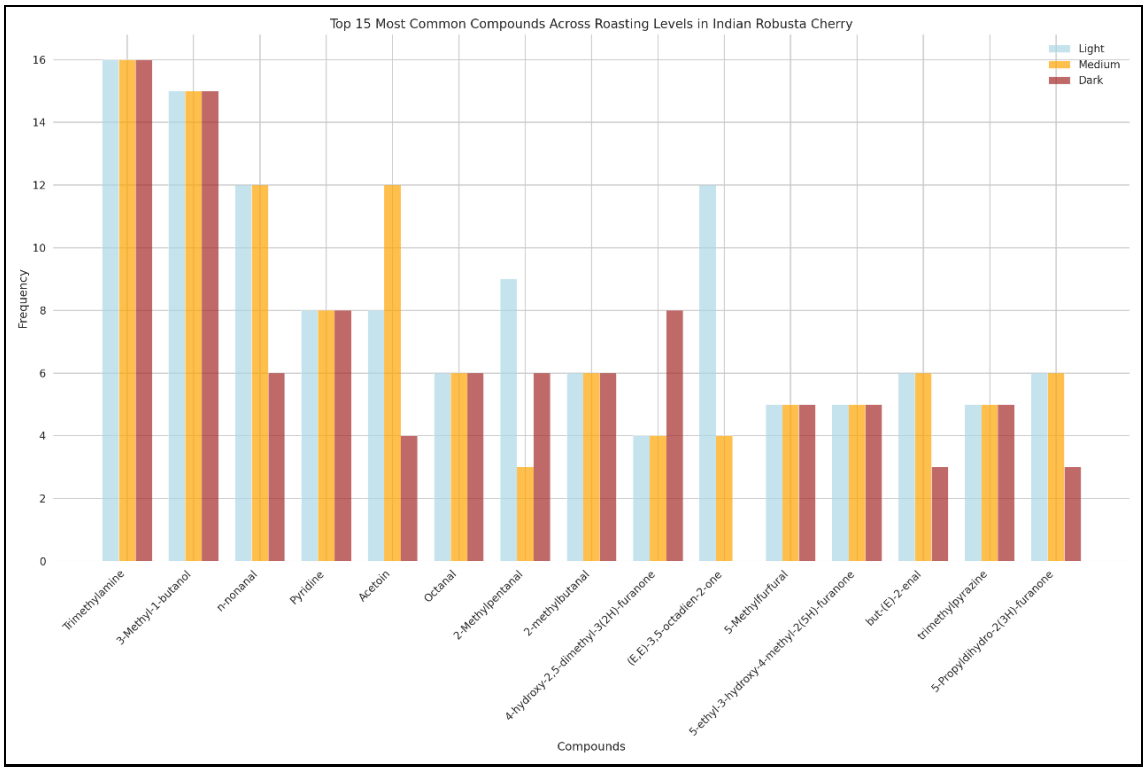

Fig 10: Common Volatile Chemical compounds across different Roast profiles of Indian Robusta Cherry

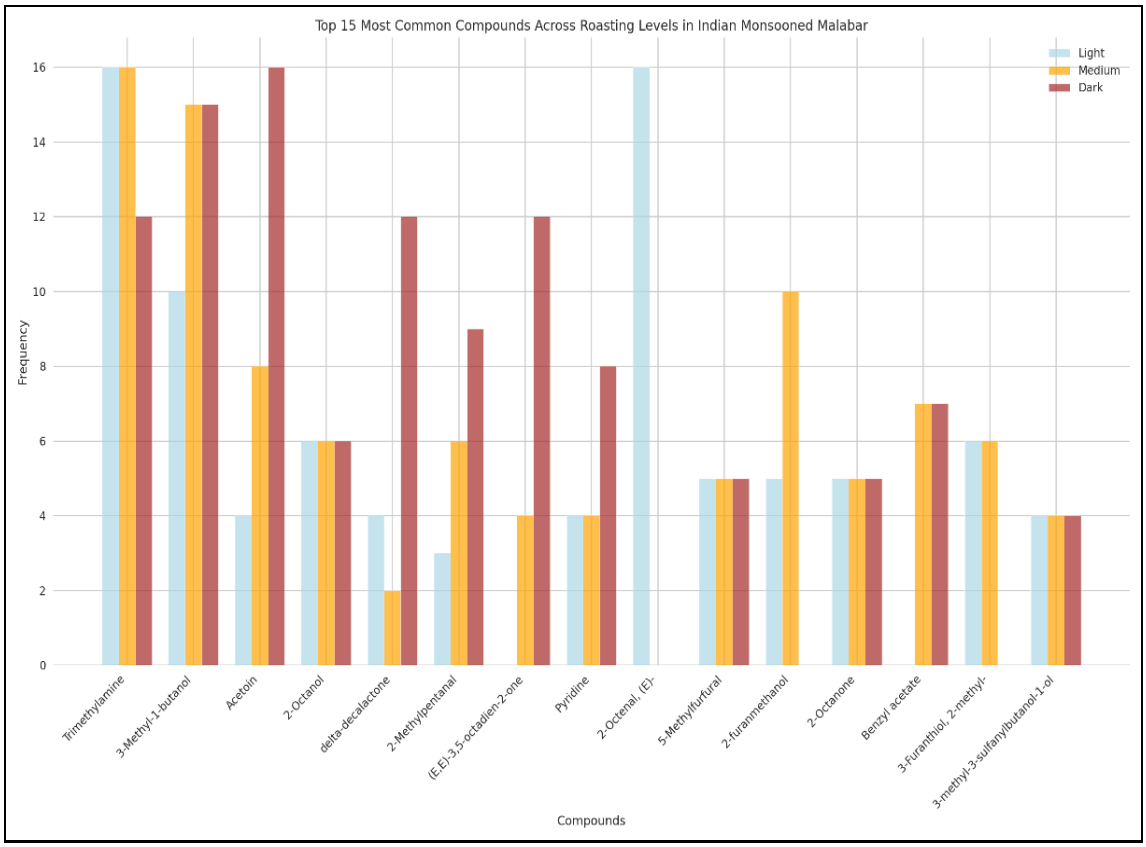

Fig 11: Common Volatile Chemical compounds across different Roast profiles of Indian Monsooned Malabar

Timethylamine, Acetoin, and 3-Methyl-1-butanol are the most common compounds across all types of coffee, contributing to general freshness, creaminess, and fruity aromas. Indian Robusta coffee (Fig 9 & 10), whether in Cherry or Parchment form, displays a more bitter chocolate and earthy profile with compounds like Pyridine and gamma-nonalactone. Indian Arabica types (both Parchment and Cherry) feature compounds contributing to lighter, more floral, and fruity flavors. Indian Arabica Parchment (Fig.7) and Arabica Cherry (Fig.8) are notable for higher presence of Eugenol, which contributes to spicy flavors, and Methanethiol, which is often linked to a sulfurous aroma. Previous studies have shown that the extent of roasting impacts the presence of compounds such as Acetoin,

Eugenol, and 3-Methyl-1-butanol. These compounds contribute to flavors such as creamy, spicy, and fruity characteristics, respectively [2].

Acetoin, a compound often linked to creamy, buttery, and smooth characteristics, showed increased frequency across all coffee types in medium and dark roasts [18]. Indian Arabica Parchment (Fig. 7) and Indian Robusta Parchment (Fig. 9) displayed significant relevance for this compound in dark roasts, indicating the development of richer, smoother profiles typical of darker roasts. Indian Robusta Cherry (Fig.10) demonstrated an increase in acetoin as the roast level progressed, aligning with the development of a fuller-bodied cup.

Indian Monsooned Malabar coffee (Fig, 11) shows a distinctive spice and earthy profile due to compounds like 2-Octenal. According to Petracco [2], the Monsooned Malabar coffee has a mellow, earthy, and spicy flavor, with Eugenol and 2-Octenal being prominent compounds. These findings were confirmed in the present study, where Monsooned Malabar coffee exhibited unique extraction patterns that differed from both Arabica and Robusta varieties, aligning with its distinctive flavor profile.

The results from the analysis of these five coffee types demonstrate how roasting significantly alters the chemical composition of coffee beans. While light roasts retain more grassy and fruity compounds, medium and dark roasts emphasize spicy, earthy, and caramelized characteristics, with compounds such as Acetoin and Eugenol playing a major role in the development of smoothness and spice.

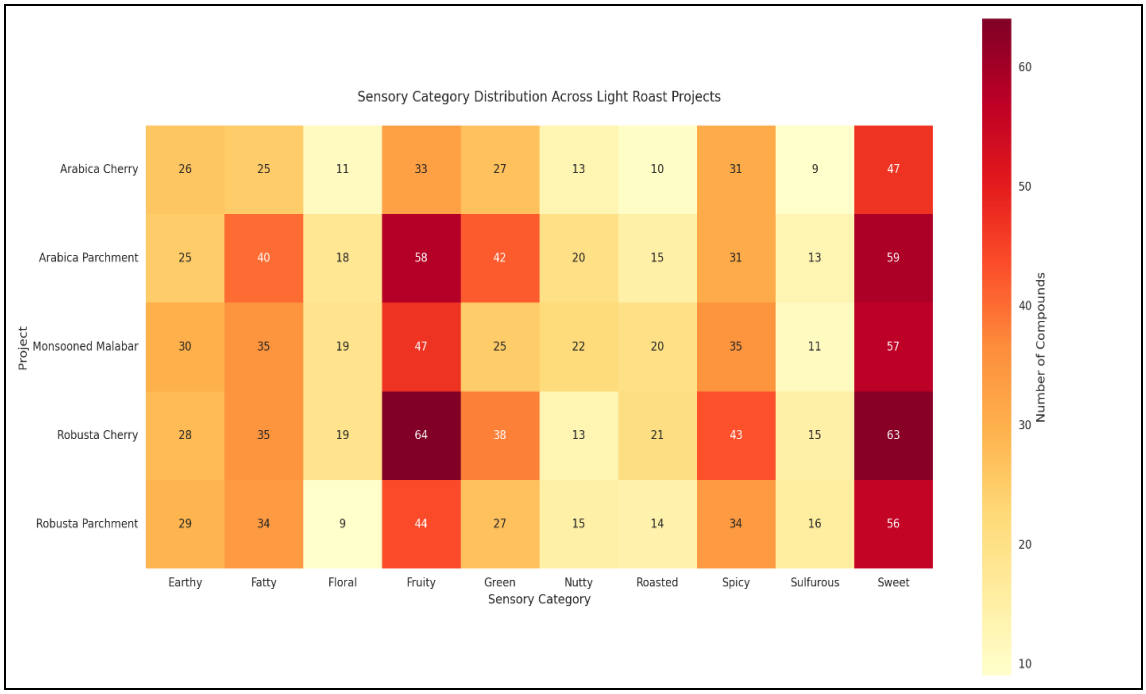

Fig 12: Heat map of Sensory category distribution across light roast profile of Indian coffee varieties

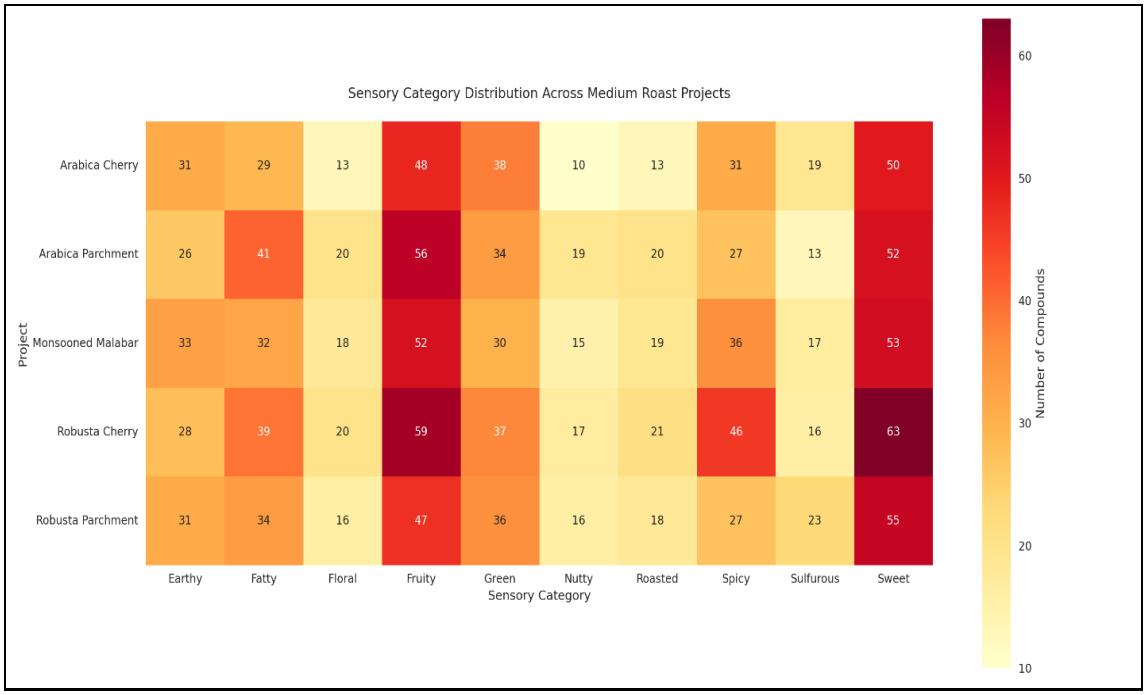

Fig 13: Heat map of Sensory category distribution across Medium roast profile of Indian coffee varieties

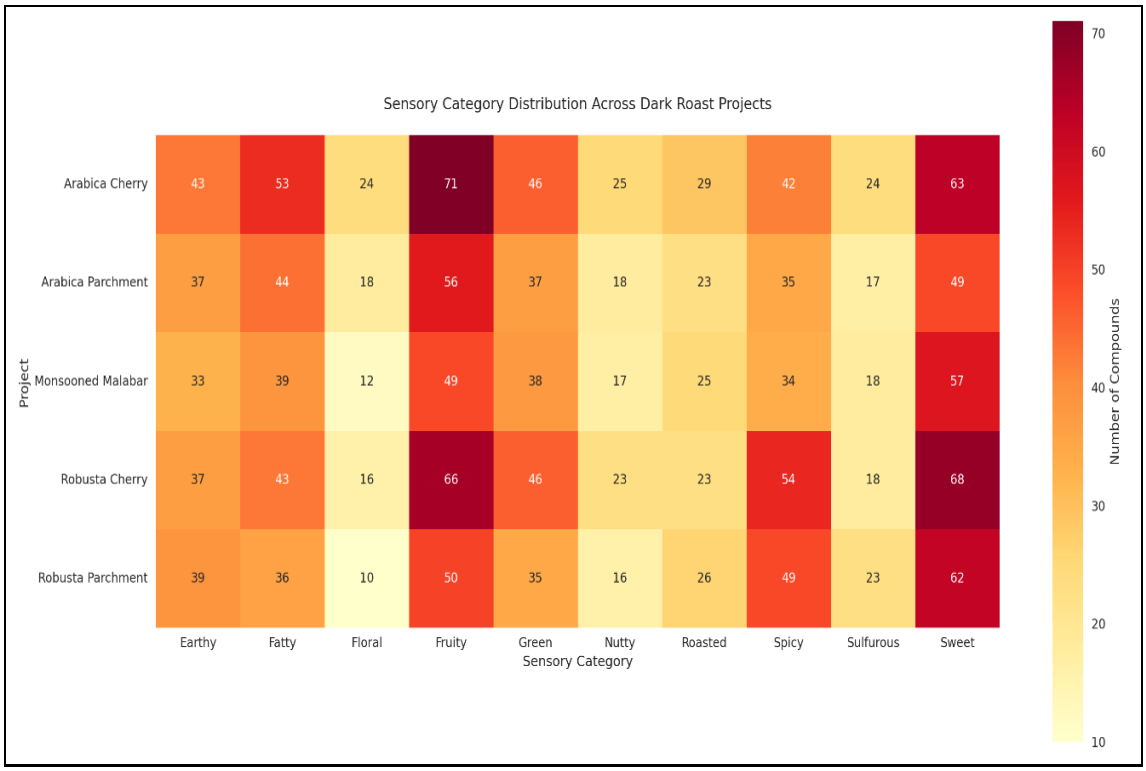

Fig 14: Heat map of Sensory category distribution across Dark roast profile of Indian coffee varieties

These heatmaps (Fig. 12 to 14) effectively demonstrate the evolution of sensory profiles across different roast levels and coffee varieties. While Arabica beans are marked by sweet and fruity characteristics, Robusta beans display more earthy, roasted, and bitter tones, particularly in dark roasts. Monsooned Malabar coffee stands out for its balanced and complex flavor profile, with an increasing emphasis on earthy and roasted flavors as roasting progresses.

Conclusion

This study comprehensively investigated the extraction dynamics of five Indian coffee varieties—Arabica Cherry, Arabica Parchment, Robusta Cherry, Robusta Parchment, and Monsooned Malabar—under varying roast profiles (light, medium, dark) and grind sizes (coarse, medium, fine). It was observed that light and medium roasts consistently exhibited moderate extraction yields (19-21%), which could be attributed to their higher solubility of lighter compounds during extraction. Dark Roasts, however, showed greater variability in extraction yield, with a broader range from 17.8% (coarse grind) to over 23% (fine grind).Grind size was the most influential factor affecting extraction yield. Arabica varieties (both Cherry and Parchment) demonstrated consistently higher extraction yields than Robusta beans, which could be attributed to their finer bean structure and higher solubility. Arabica coffees also exhibited a more fruity and floral volatile compound profile, indicating that they release more of their aromatic compounds during extraction. Robusta coffees, particularly Robusta Cherry and Robusta Parchment, showed more earthy and bitter characteristics due to the higher density and lower solubility of certain compounds. Monsooned Malabar coffee, with its unique post-harvest processing, exhibited distinct extraction behavior with lower TDS values and a different volatile profile.

The increased moisture content and bulk density of Monsooned Malabar beans resulted in altered extraction dynamics, with the coffee retaining a more earthy and spicy profile even in light roasts. Volatile compounds such as Acetoin, Eugenol, and 3-Methyl-1-butanol were significantly more prominent in dark roasts, contributing to the smoothness, spiciness, and fruity notes associated with darker coffee profiles. Methanethiol were more abundant in light roasts and contributed to grassy and sulfurous flavors. The Maillard reaction and caramelization in darker roasts led to the formation of compounds like Eugenol and Furanones, enhancing spiciness and caramelized characteristics in the final cup.

Indian Arabica coffees (e.g., Coorg, Chikmagalur) are often best brewed with medium grind and light to medium roasts to preserve their fruity, sweet characteristics. The fine structure and lower density allow for more efficient extraction at medium grind sizes. Indian Robusta is often used in espresso blends or for traditional Indian filter coffee. In case of standalone Robustas coarse grind for brewing with traditional drip methods and a medium to dark roast will yield the good results. Due to its unique processing, this coffee requires special attention in brewing. The high moisture content and bulk density require longer extraction times, even at coarser grinds. A slightly coarser grind with a longer brew time will help achieve a smoother, less bitter taste profile. Since it has more earthy, spicy notes, these coffees perform well with medium roast profiles.

Given the significant findings on the impact of roasting, grind size, and coffee variety on extraction dynamics, future studies could focus on optimization of brewing techniques, Investigating how extraction dynamics correlate with sensory attributes in different roast profiles to better align brewing methods with consumer taste preferences, exploring alternative post-harvest processing techniques and their effect on the physical and chemical properties of coffee beans, particularly for Monsooned Malabar and specialty coffees.

By focusing on these areas, future research can help improve quality control, roast profiling, and brewing techniques, ensuring that coffee producers and consumers alike can achieve consistent, high-quality brews with tailored flavor profiles.

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Conflict of Interest Declaration
The authors declare that there are no conflicts of interest related to this work.

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