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Multivariate analysis of soluble compound extraction efficiency from coffee under cold brew conditions

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Abstract
The aim of this study was to evaluate the efficiency of soluble compound extraction from coffee using three cold brew process variants, addressing both technological and environmental aspects of this production method. Experiments were conducted with a custom-designed extraction basket and a forced-flow liquid system to ensure uniform raw material extraction. The process was carried out at temperatures not exceeding 30 °C, and the concentrations of total dissolved solids (TDS) and extraction yield (EY) were analyzed. Results showed that secondary extraction recovered up to 31.8% of the initial TDS, while replacing water with an enriched extract improved efficiency by 36.2%. The highest EY values (above 26%) were obtained in multistage variants, with a maximum TDS concentration of 2.65%. A short, 3–4-minute secondary extraction ensured effective performance, reducing the total process time to approximately 60 minutes – much shorter than the traditional 24-hour cold brew method – without loss of efficiency. The shorter process duration and its operation under low-temperature conditions can potentially improve efficiency and help reduce energy and water consumption, which in turn may also contribute to enhanced sustainability and resource efficiency in cold brew coffee production.

Keywords
cold brew coffee, solid–liquid extraction, total dissolved solids (TDS), coffee extraction efficiency

1. INTRODUCTION

Coffee has played a pivotal role in global trade, culture, and daily life for centuries. Its economic and social significance extends far beyond a simple beverage, influencing consumption patterns, production practices, and market dynamics worldwide.

1.1. Global significance of coffee

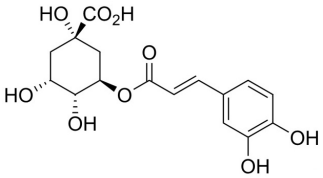
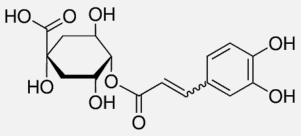
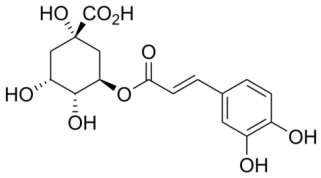
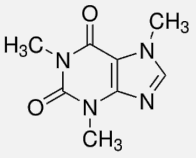
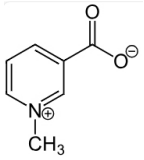
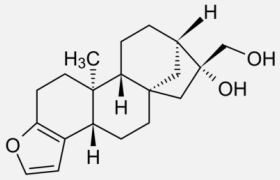
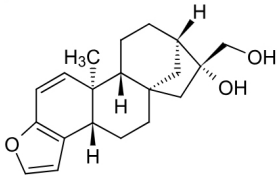
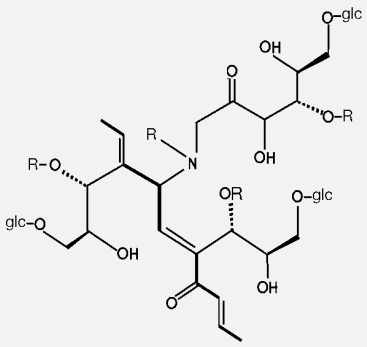
Coffee is one of the most highly commercialized non-alcoholic food products in the world and, after crude oil, the second most valuable traded commodity on the global market. It constitutes an important element of modern lifestyles. In the European Union countries, the average annual coffee consumption per capita is 5.1 kg, which is comparable to that in the United States (Bae et al., 2014). Coffee beverages are most commonly prepared using two coffee species – *Coffea arabica* and *Coffea canephora* (Robusta). Among these, Arabica, accounting for about 70–75% of global production, is distinguished by its complex aroma–flavour profile and high sensory quality (Cruz O'Byrne et al., 2020; Ngugi et al., 2021). Coffee is also the most widely consumed beverage with pharmacological activity, owing to its rich content of bioactive compounds (Aytar and Aydın, 2025; Zarebska et al., 2022). Its popularity is driven not only by taste, aroma, and caffeine content but also by its complex chemical composition, which contributes to both sensory and functional properties (Machado et al., 2024).

1.2. Chemical composition and bioactive compounds of coffee

Coffee beans are chemically complex, containing an estimated 1,000–2,000 distinct compounds, with their composition influenced by botanical origin, cultivation conditions, and processing methods such as roasting or fermentation. A critical review of the literature identified the compounds most frequently reported in peer-reviewed studies as relevant to the bioactivity and sensory properties of coffee (see Table 1).

The principal constituents of coffee extracts can be classified into three major chemical groups: polyphenolic acids, alkaloids, and lipids. Polyphenolic acids are predominantly chlorogenic acids, including 3–O–, 4–O–, and 5–O–caffeoylquinic acids (3–CQA, 4–CQA, 5–CQA). The alkaloid fraction is dominated by caffeine and trigonelline, while the lipid fraction primarily

Table 1. Bioactive compounds in coffee (Merck KGaA (Sigma-Aldrich), 2025; National Center for Biotechnology Information, 2025).

Coffee ingredient	Chemical structure
Chlorogenic acid (3–CQA; $C_{16}H_{18}O_9$)	
Chlorogenic acid (4–CQA; C16H18O9)	
Chlorogenic acid (5–CQA; $C_{16}H_{18}O_9$)	
Caffeine (1,3,7–trimethylxanthine; $C_8H_{10}N_4O_2$)	
Trigonelline (*N*–methyl nicotinic acid; $C_7H_7NO_2$)	
Cafestol ($C_{20}H_{28}O_3$)	
Kahweol ($C_{20}H_{26}O_3$)	
Melanoidins ($C_{17-18}H_{26-27}O_{10}N$)	

consists of cafestol and kahweol. Roasted coffee also contains melanoidins, high-molecular-weight brown polymers formed via Maillard reactions, contributing to colour, aroma, and antioxidant activity (Moreira et al., 2012; Ren et al., 2019). Their formation is influenced by the interaction of reducing sugars and amino acids during roasting, and they represent a unique class of bioactive polymers not present in green coffee.

Coffee also contains proteins, polysaccharides (galactomannans, arabinogalactans, cellulose, hemicellulose), nitrogenous compounds, vitamins, minerals (K, Mg), and soluble sugars (glucose, fructose, sucrose, xylose, rhamnose, galactose, arabinose), which undergo chemical transformations during roasting, forming bioactive compounds including melanoidins (Murai and Matsuda, 2023; Moreira et al., 2012).

Among these compounds, the most important bioactive constituents are caffeine, trigonelline, and chlorogenic acids – substances with well-documented health-promoting effects (Aytar and Aydın, 2025; Farah and de Paula Lima, 2019; Rao and Fuller, 2018; Zarebska et al., 2022).

Caffeine, the primary psychoactive compound in coffee, acts as a central nervous system stimulant, enhancing cognitive function, supporting liver metabolism, accelerating lipolysis, and influencing cardiovascular, digestive, and respiratory systems (Farah and de Paula Lima, 2019; Farias-Pereira et al., 2021). In addition to its physiological effects, caffeine contributes to the beverage's body, intensity, and approximately 10% of the perceived bitterness of brewed coffee. Trigonelline, the second most abundant alkaloid in green coffee beans, is converted to niacin (vitamin B3) during roasting. This transformation contributes to coffee's aroma and flavor, generating sweet, caramel-like, and nutty notes, and endows the beverage with hypoglycemic, neuroprotective, anti-inflammatory, and antibacterial properties (Zarebska et al., 2022). Trigonelline may also support dendrite and axon regeneration in cortical neurons and help regulate blood glucose and lipid levels. Compared to other compounds such as chlorogenic acids, trigonelline is more resistant to degradation during storage, making it a useful indicator of the long-term quality of coffee beans (Zarebska et al., 2022). Chlorogenic acids (CGA), the main phenolic compounds in coffee, are potent antioxidants with cardiovascular, anti-inflammatory, and glucose-regulating properties. They also influence coffee's sensory profile, contributing to its acidity, bitterness, and astringency (Badmos and Kuhnert, 2025; Ngugi et al., 2021; Zarebska et al., 2022). Among their isomers, 3–O–caffeoylquinic acid (3–CQA) is the most abundant. During roasting, CGAs decompose into caffeic and quinic acids, shaping the characteristic taste and aroma of coffee. The content of CGA in coffee beans is influenced by post-harvest processing and storage conditions, including processing type (washed vs. natural), roasting degree, and storage duration. Higher roasting temperatures and prolonged storage generally lead to a reduction in CGA levels, as reported by Zarebska et al. (2022) and Badmos and Kuhnert (2025).

In addition to these compounds, coffee lipids play a crucial role in the beverage's sensory characteristics. They influence foam stability, help retain volatile aroma compounds, and contribute directly to flavour. Key diterpenes, including cafestol, kahweol, and 16–O–methylcafestol, further enrich the sensory profile of brewed coffee (Makiso et al., 2023; Ren et al., 2019). A cup of unfiltered coffee typically contains about 3–6 mg of each of these diterpenes (Makiso et al., 2023; Ren et al., 2019).

1.3. Technological factors affecting coffee quality

Coffee quality is influenced by multiple factors, including the plant's genetic variety, region of origin, environmental growing conditions, harvesting techniques, post-harvest processing, and roasting profile (Maksimowski et al., 2023). These parameters determine the chemical composition of coffee, shaping the concentration of bioactive compounds as well as its flavor, aroma, and overall sensory quality. In the specialty coffee segment, consistency and uniformity of flavor are essential, with coffees scoring ≥ 80 points on the Specialty Coffee Association (SCA) scale recognized as top-quality (Córdoba et al., 2019). These coffees are characterized by verified origin, carefully selected processing methods, appropriate roasting profiles, and professional serving techniques. These attributes are fundamental evaluation criteria for both informed consumers and coffee industry professionals. For cold brew preparation, beans roasted at 210–220 °C provide optimal results (Maksimowski et al., 2023). While hot-water extraction at near-boiling temperatures allows rapid extraction of soluble compounds (18–35%) (Córdoba et al., 2019), specialty coffee emphasizes precise control over sensory consistency, verified origin, and careful processing methods.

1.4. Cold brew coffee: market trends, production challenges, and circular economy opportunities

A wide variety of coffee beverages is available on the market, most of which are produced through hot-water extraction using near-boiling temperatures, allowing the process to be completed within a few minutes (Córdoba et al., 2019). The efficiency of soluble compound extraction depends, among other factors, on the brewing method and the grind size of the coffee beans, which influence the amount of substances transferred into the solution.

Cold brew coffee – prepared by prolonged contact between ground coffee and water at room temperature or lower – is growing in popularity due to its milder flavor, reduced acidity, and natural sweetness, which appeal especially to Generation Z consumers and those sensitive to traditional coffee bitterness (Córdoba et al., 2021). According to market forecasts, the global value of the cold brew coffee market is expected to reach 1.63 billion USD by 2025. Owing to these qualities, cold brew is perceived as a higher-quality beverage,

particularly appealing within the premium segment. With the rapid expansion of the Ready-To-Drink (RTD) beverage market, canned or bottled cold brew has become one of the leading categories of innovative coffee products. Despite this growth, standardized brewing protocols are lacking, resulting in wide variations in temperature, extraction time, coffee-to-water ratio, and filtration method (Cerca et al., 2023; Claassen et al., 2021).

Traditionally, cold brew coffee is produced as a batch process based on slow, static extraction, either through full immersion or via slow percolation at 20–25 °C for 6–24 hours (Angeloni et al., 2019; Fuller and Rao, 2017; Zhang et al., 2022). This method, while yielding a beverage with distinctive sensory properties, is time-consuming and economically inefficient, limiting commercial scalability. Commercial systems typically have small capacities (1–5 L) and long extraction times (18–24 h), though market expansion will require larger systems (20–30 L), increasing operational costs and refrigeration needs (Chiu et al., 2024). Consequently, there is a pressing need to develop faster, more efficient, and continuous extraction methods that can meet rising market demand, optimize production efficiency, and maintain product quality. In response to the growing demand for cold brew coffee – observed in both retail and food service sectors – solutions are being explored to reduce extraction time and improve process efficiency.

Implementing cold brew production on an industrial scale also requires precise control of process parameters and reproducibility, presenting significant technological challenges. At the same time, cold brew production offers opportunities to extract bioactive compounds at lower temperatures, supporting the development of functional beverages and low-sugar alternatives. Efficient raw material management is critical due to rising coffee costs and scarcity. This need is further amplified by environmental and economic pressures, including climate change, resource depletion, energy costs, and tightening regulations.

After cold brew extraction, a substantial portion of valuable chemical compounds – such as caffeine, polyphenols, chlorogenic acids, and non-reducing sugars – remains in spent coffee grounds (SCG). Traditionally treated as waste, these residues represent an underutilized resource. From a circular economy perspective, their reuse can reduce waste, lower the carbon footprint, and recover high-value compounds, supporting sustainability goals and maximizing efficiency and product quality in modern coffee production (Biłos et al., 2025; Colantoni et al., 2021; Hnydiuk-Stefan et al., 2024; Vo et al., 2023). In light of the technological and environmental challenges discussed above, this study aimed to:

1. Identify process conditions that maximize the extraction of soluble compounds from coffee.
2. Enhance the efficiency of the cold brew method.
3. Investigate the potential reuse and valorization of spent coffee grounds (SCG).

Experiments were carried out in a 28 L tank equipped with a specially designed extraction basket, ensuring uniform water flow and effective separation of the coffee bed from the liquid phase. This setup allowed both optimized extraction and the recovery of SCG for potential valorization.

2. COLD BREW COFFEE: PRODUCTION METHODS AND EXTRACTION MECHANISM

The extraction of soluble compounds from coffee at low temperatures defines the cold brew process, influencing the beverage's chemical composition, flavor, and aroma. A thorough examination of production techniques and underlying extraction mechanisms provides insight into improving yield, consistency, and sensory attributes.

2.1. Fundamentals of cold brew extraction

The typical stages of cold brew production include immersing ground coffee in water, mechanically mixing the suspension to ensure effective phase contact, and then separating the brew from the solid residue (coffee grounds), usually by means of gravity or pressure filtration. Coffee brewing is a solid–liquid extraction process in which ground coffee beans (solid phase) come into direct contact with water (liquid phase) – see Fig. 1. Water, acting as a solvent, enables the migration of chemical compounds from the bean matrix into the solution. This process relies on the selective dissolution of substances present in the solid sample; therefore, the efficiency of extraction mainly depends on the solubility of specific compounds in water.

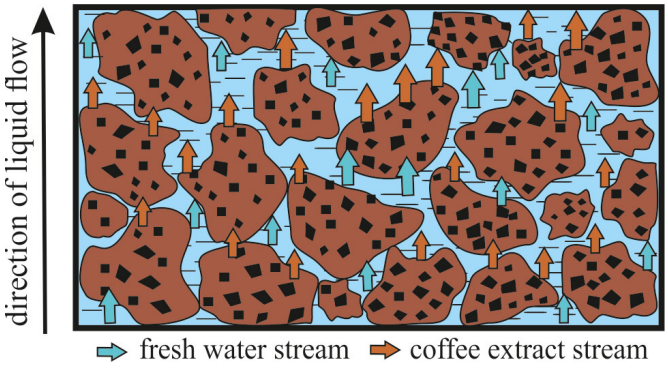


Figure 1. Solid–liquid extraction. Structure of the porous layer – the extracted substance is located within the particles of the ground porous material.

In most cases, solid–liquid extraction is time-consuming, which is why a continuous extraction mode is considered most advantageous. To ensure the process runs efficiently, the raw material (in this case, coffee beans) must be properly prepared – e.g., by grinding and disrupting the structure of the plant tissue.

2.2. Technological approaches to cold brew coffee production

The final sensory properties of the coffee brew are influenced by both dissolved and suspended components (Córdoba et al., 2020). Numerous alternative technological approaches to cold brew coffee extraction have been described in the literature. These methods differ in their mechanisms of action and implementation potential. They are primarily aimed at reducing extraction time and improving efficiency while maintaining or enhancing the sensory quality of the beverage Maksimowski et al., 2023; Zwicker et al., 2024). Among the most frequently described methods are:

- immersion extraction with or without agitation, which increases the interfacial contact area and accelerates mass transfer (Ahmed et al., 2019; Claassen et al., 2021; Córdoba et al., 2019; Maksimowski et al., 2023),
- microwave-assisted extraction (MAE), utilizing rapid internal heating of coffee particles to enhance the diffusion of soluble compounds (Caudill et al., 2022),
- percolation extraction, involving pre-soaking of the raw material followed by solvent percolation through the coffee bed (Stanek et al., 2021),
- laser-assisted extraction, a novel technique that uses picosecond laser pulses to release compounds from coffee grounds (Ziefuß et al., 2022),
- ultrasound-assisted extraction (UAE), based on cavitation effects that improve penetration and solubility of active components (Chiu et al., 2024; Claassen et al., 2021; Liu et al., 2024; Özdemir et al., 2025; Putro et al. 2021; Yang et al., 2024),
- drip cold brew method, a slow percolation technique conducted at low temperature (Ahmed et al., 2019; Angeloni et al., 2019; Córdoba et al., 2021),
- high-pressure processing (HPP), which disrupts cellular structures and facilitates the release of soluble compounds (Zhang et al., 2022),
- experimental methods, including vacuum cycling, freezing, chaotropic salt addition (e.g., Mg^{2+}), and lyophilization, used primarily to enhance solubility and extractability (Kyroglou et al., 2021; Kyroglou et al., 2022; Wang et al., 2024).

2.3. Influence of technological parameters on extraction efficiency

Numerous studies indicate that the efficiency of coffee extraction depends on various technological factors, such as extraction temperature, grind size and particle dimensions of ground coffee, porosity and structure of the coffee bed, phase contact time, roasting profile, brew ratio (mass of dry coffee to water volume), and the chemical composition of the solvent used (Moroney et al., 2016a; Moroney et al., 2016b; Rao et al., 2020; Zakaria et al., 2023).

Some researchers suggest that the presence of magnesium (Mg^{2+}) and calcium (Ca^{2+}) ions in water may enhance the extraction efficiency of soluble compounds from coffee without negatively affecting its sensory profile (Hendon et al., 2014). On the other hand, other reports indicate that the course of the extraction process is largely independent of the mineral composition of the water (Bratthäll et al., 2024).

Fuller and Rao (2017) point out that the efficiency of coffee extraction largely depends on the particle size distribution and the porosity structure of the coffee bed, which determine the conditions for mass transfer and liquid flow within the extraction system. This distribution affects both the surface area available for contact with the solvent and the permeability of the coffee layer. Medium-ground samples typically exhibit a broader particle size range, whereas coarse-ground samples tend to show a more uniform distribution.

Both the internal porosity of individual particles and the interstitial (inter-particle) porosity are important, as they influence the diffusion of chemical compounds and fluid flow, and thus the overall extraction efficiency. According to the authors (Fuller and Rao, 2017), larger particles are associated with longer diffusion paths, which prolong the migration time of solutes into the liquid phase. In turn, poorly sorted coffee beds (i.e., with wide grain-size variation) create more tortuous and less permeable pore networks, which restrict liquid flow and further slowdown the transport of soluble substances.

The chemical compounds present in coffee differ in polarity and solubility, which affects the rate at which they are extracted. Higher temperatures increase solubility and promote the release of volatile aromatic compounds. Fuller and Rao (2017) demonstrated that, during cold brew extraction, the concentrations of chlorogenic acid and caffeine rise rapidly within the first 180 minutes, reaching equilibrium after approximately 400 minutes, regardless of the degree of roast or grind size.

2.4. Comparative analysis of extraction techniques

Córdoba et al. (2019) used the indirect immersion method (20 °C, 60 g coffee per 700 g water, $\sim 1:12$ ratio) to examine the effects of extraction time, coffee origin (Nariño and Huila Colombian specialty coffees), and grind size (medium: 501–700 µm; coarse: 701–900 µm) on the physicochemical properties of cold brew coffee. TDS values ranged from 0.71 % (medium grind, 14 h) to 2.04 % (coarse grind, 22 h), with corresponding extraction yields (EY) between 7.06 % and 20.39 %. They reported that grinding degree had the greatest impact on cold brew properties, followed by extraction time, while origin mainly affected acidity and pH. The brews prepared for 14 h with coarse grind were most preferred for their sweet, fruity–floral, and creamy profile.

Rao et al. (2020) prepared cold brew coffee using 20 g of coffee grounds and 200 mL of deionized water (coffee-to-water ratio 1:10; 100 g/L) at room temperature and steeped the mixture for 7 h in a French press. In their study, TDS values ranged from 1.88% for the lightest roast (194 °C) to 2.06% for the darkest roast (209 °C), indicating a slight increase in solubility with roast degree.

Zakaria et al. (2023) investigated the effects of brewing parameters on cold brew coffee (CBC) properties using a response-surface methodology. Key factors examined included water temperature (4–30 °C), coffee-to-water ratio (62.5–166.7 g·L^{-1}), coffee mesh size (0.25–0.71 mm), and extraction time (7–24 h). Their results showed that these parameters significantly influenced total dissolved solids (TDS), with TDS values ranging from 1.19% to 3.99 %. Under specific conditions (water temperature 17 °C, coffee concentration $\simeq$ 114.6 g·L^{-1}, particle size 0.71 mm, extraction time 15.5 h), a TDS of 2.32 % was observed. CBC produced under optimized conditions exhibited higher caffeine content and greater concentrations of volatile compounds and organic acids compared to hot-brewed coffee at equivalent TDS.

Ziefuß et al. (2022) developed an innovative method for ultrashort cold brew extraction using a picosecond laser, enabling the achievement of comparable concentrations of caffeine and aromatic compounds in just 3 minutes – without the need for heating. A three-minute irradiation resulted in only a slight temperature increase (3–5 °C), allowing the process to remain within cold brew conditions. However, the use of longer laser pulses was associated with the risk of overheating and degradation of coffee compounds.

In turn, studies by Caudill et al. (2022) showed that the use of microwave-assisted technology can significantly accelerate the cold brew production process, offering comparable chemical and sensory quality of the beverage while reducing extraction time compared to conventional methods.

Ultrasound accelerates the extraction process through the phenomenon of acoustic cavitation. The collapse of cavitation bubbles near coffee particles generates high-pressure microjets that damage cellular structures, facilitating the release of intracellular compounds.

Putro et al. (2021) showed that ultrasound-assisted cold brew coffee extraction enables a significant increase in phenolic, flavonoid, and caffeine content under optimized conditions of 25 °C extraction temperature, 15 min extraction time, 80 s^{-1} ultrasound duty cycle, and medium grind size. Maksimowski et al. (2023) examined cold brew coffee beverages produced by ETNO Café (Wrocław, Poland) using Arabica coffee from Brazil roasted to a medium profile. Coarsely ground beans with a particle size of 1.5–2.0 mm were extracted by immersion in reverse osmosis water in stainless-steel tanks equipped with a 3.0 kW overhead mixer. The extraction was carried out until achieving a TDS of 1.3% after 12 hours, followed by filtration through a 200 µm filter and HTST pasteurization. Given the extended extraction time (12 h) required to obtain a relatively low TDS value (1.3%), Zhai et al. (2022) developed a novel ultrasound-assisted cold brewing (UAC) method, which significantly shortened the process to 1 hour. Under optimized conditions – a coffee-to-water ratio of 1:15, an extraction time of 60 min, and an ultrasonic power of 200 W – the UAC method achieved an extraction yield (EY) of 17.72%, with TDS values 6–26% higher than those obtained in conventional static cold brews (TDS = 1.43–1.64%). The concentrations of total lipids, proteins, and titratable acids also increased by 10–31%, demonstrating improved extraction kinetics. The aroma profile of UAC coffee was similar to that of traditional cold brew, but the shorter process reduced degradation of thermolabile compounds.

In a similar study, Liu et al. (2024) demonstrated that countercurrent ultrasound-assisted extraction enables high efficiency in a significantly shorter time. At a coffee-to-liquid ratio of 1:15 and an extraction time of 50 minutes, a TDS of 1.63% and an extraction yield of 20.52% were achieved – representing an 83.33% increase in efficiency compared to the conventional 5-hour process.

Chiu et al. (2024) reported more than a twofold increase in extract yield (EY) within less than 3 minutes using a 100 W ultrasonic reactor. EY increased from 18.04% to 33.44% when the basket loading percentage was reduced from 100% to 33%. The authors indicated that localized temperature rise caused by cavitation, combined with intense mixing, significantly enhanced mass transfer and accelerated saturation of the extract. The authors demonstrated that the application of ultrasound significantly enhanced caffeine extraction in the brew. Caffeine concentrations in sonicated samples ranged from 1.34 to 1.84 mg/mL, whereas control samples exhibited lower concentrations, ranging from 0.74 to 1.1 mg/mL. Chiu et al. (2024) reported that fatty acid concentrations in sonicated samples were higher than in control samples and increased with decreasing Basket Loading Percentage (BLP), whereas concentrations in the control samples remained nearly constant ($\sim$ 1.16 mg/mL). This trend, consistent with extraction yield (EY), suggests that ultrasound is more effective at lower basket loadings, likely due to enhanced acoustic cavitation in the presence of a higher water proportion.

Chen et al. (2023) used conventional cold brew coffee extracted at 0.1 MPa for 12 h as the control, reaching a TDS of 1.11%. When Ultra-High Pressure (UHP) – assisted extraction was applied, increasing pressure ($>$ 300 MPa) and holding time ($>$ 20 min) led to higher TDS values, rising from 1.11% to 1.22–1.24%, and an increase in extraction yield (EY**)**. The observed effect was attributed to cell wall disruption and increased membrane permeability under high pressure and ultrasonic action (sonoporation), which facilitated faster diffusion of soluble compounds into the extract. This process compensated for the long extraction times typical of static cold brewing, allowing TDS and EY comparable to conventional cold brews to be achieved within 20 minutes. However, despite these advantages, Chen et al. (2023) reported that while chlorogenic acids (CGA) could be extracted more rapidly under UHP conditions (10–30 min), their total concentrations remained lower than those obtained by conventional cold brewing under atmospheric pressure. Similarly, changes in trigonelline content followed a different pattern than in traditional brews. Sensory evaluation revealed that UHP-assisted

cold brew coffee exhibited greater sweetness and cleanliness with a softer taste, but lower overall flavor intensity compared to conventional cold brew, likely due to reduced extraction of volatile aroma compounds during the shorter process.

Stanek et al. (2021) demonstrated that the percolation-based Hardtank method, applied for 30 minutes (19.3 °C), yielded beverages with higher sensory quality and health-promoting properties compared to the traditional 24-hour cold brew method. Samples obtained using this technique contained up to four times more lipids than those from classic cold brew and up to five times more than hot brew coffee, contributing to an enhanced aroma and flavor profile. Additionally, they showed higher antioxidant activity and greater phenolic content.

Studies by Zwicker et al. (2024) confirmed the feasibility of performing a continuous cold brew coffee extraction process under laboratory conditions using an innovative method combining counter-current extraction with a single-helix screw and mechanical pressing of the spent grounds. The developed process model shows strong potential for industrial-scale implementation, offering several technological advantages, including improved quality control, reduced unit costs, and enhanced hygiene and reproducibility of production.

Maceration is governed primarily by molecular diffusion, wherein soluble compounds migrate from regions of higher concentration (adjacent to the surfaces of ground coffee particles) to regions of lower concentration (in the surrounding aqueous phase). The rate of extraction is dependent on the concentration gradient, which progressively decreases as equilibrium is approached and solute concentrations become uniform throughout the system.

In contrast, percolation techniques maintain a continuous flow of solvent through the coffee bed, which facilitates the constant renewal of the low-concentration boundary layer. This allows the system to sustain a favorable concentration gradient and thereby enhance mass transfer. According to Fick's first law of diffusion, such conditions are conducive to efficient and continuous migration of solutes from the solid to the liquid phase.

Beyond diffusion, advective transport mechanisms – defined as solvent-driven displacement of solutes – also contribute significantly to extraction kinetics. The continual removal of the saturated liquid phase enables the maintenance of elevated extraction rates throughout the process.

One of the fundamental distinctions between maceration and percolation lies in the duration of extraction. While immersion-based cold brew processes typically require up to 24 hours, percolation-based methods can achieve comparable or superior extraction within 30 to 120 minutes. This enhanced efficiency has direct implications for industrial scalability, enabling real-time or on-demand production of cold brew coffee in commercial environments such as cafés and restaurants.

2.5. Valorization of spent coffee grounds

As global coffee consumption continues to rise, the volume of spent coffee grounds (SCG) generated as a by-product is also increasing. This trend has stimulated growing research and industrial interest in SCG applications across households, cosmetics, agriculture, environmental management, and energy sectors. The utilization of SCG supports the principles of the circular economy, reduces environmental impact, and fosters innovation in waste management and resource efficiency. Valorization of SCG is increasingly recognized not only as an effective waste management strategy but also as a source of sustainable innovation and economic value within the coffee sector and beyond.

SCGs represent a significant biomass by-product of coffee production and consumption. Their effective management is widely regarded as a critical component of circular economy practices and sustainable resource utilization. Recent literature highlights the multifaceted potential of SCG as a secondary raw material across diverse sectors, including cosmetics, agriculture, biotechnology, energy, and environmental engineering (Biłos et al., 2025; Colantoni et al., 2021; Hnydiuk-Stefan et al., 2024; Vo et al., 2023). Their valorization not only contributes to waste reduction but also leverages their intrinsic chemical and functional properties – such as antioxidant activity, nutrient content, and adsorptive capacity – for high-value applications. SCGs can be valorized through multiple pathways, including household applications, cosmetics, biodegradable materials, agricultural amendments, and energy production.

2.5.1. Household applications

Dried SCGs, rich in caffeine, essential oils, and polyphenolic compounds, exhibit natural insect-repellent, odor-neutralizing, and moisture-absorbing properties. When placed in sachets or dispersed near plants, they can deter ants and other pests. SCGs have also been explored as a natural anti-slip agent on icy surfaces, offering a biodegradable alternative to conventional de-icing materials. However, their effectiveness is limited to thick ice and may require frequent reapplication. Residual organic matter can leave deposits and attract wildlife, which limits its widespread use in urban areas.

2.5.2. Cosmetic and dermaceutical applications

SCGs retain substantial quantities of bioactive compounds post-extraction, including caffeine, chlorogenic acid, trigonelline, flavonoids, and phenolic acids (Biłos et al., 2025). Solvent extraction of coffee oil from dried SCG (drying at 70 °C, using ethanol–water 1:1 or methylene chloride) yields fractions with pronounced antioxidant, anti-inflammatory, and skin-regenerating properties. These extracts have been successfully incorporated into natural exfoliants and delivery

systems for active ingredients in commercial cosmetic formulations. The development of SCG-based products by BJB COSMETICS (Opole, Poland) demonstrates the industrial viability of this approach and its alignment with circular economy principles.

2.5.3. Agricultural and biotechnological applications

SCGs have potential as a substrate for cultivating edible mushrooms, as a component of mixtures with bottom ash (BA) to improve poor or degraded soils, and for converting spent cultivation substrate into nutrient-rich fertilizer. Hnydiuk-Stefan et al. (2024) reported that SCGs, combined with straw and small additions of BA from coal-fired power plants, provide a nutrient-rich medium suitable for the mycelial growth of oyster mushrooms (*Pleurotus ostreatus*). BA additions (1–5%) improved substrate aeration and reduced acidity, while decreasing heavy metal concentrations (Cr, Ni, Pb) and increasing beneficial elements (P, Cu, Zn). Post-cultivation substrates can be repurposed as organic fertilizers, further enhancing the sustainability of this valorization pathway.

2.5.4. Energy and environmental engineering applications

SCGs can be used for biodiesel production, as a source of sugars, as a precursor for activated carbon, or as a sorbent for metal removal. Their high organic content, favorable calorific value, and potential for conversion into biofuels such as biogas, bioethanol, and biodiesel make them a valuable raw material in bioenergy systems. Colantoni et al. (2021) demonstrated that SCG pellets – either pure or blended with sawdust (15–66%) and starch (2%) – are suitable for thermal conversion processes due to high calorific value (HHV $\simeq$ 22–22.4 MJ/kg) and low ash content. Additionally, SCG serve as precursors for activated carbon and low-cost adsorbents for environmental remediation. Vo et al. (2023) confirmed their efficacy in removing rhodamine B and other industrial dyes from aqueous solutions, highlighting their potential in water and wastewater treatment without requiring chemical modification.

2.5.5. Commercial and industrial product development

Innovative applications include biodegradable consumer goods. Companies such as Kaffeeform (Germany) have developed reusable tableware – cups, mugs, and containers – manufactured from SCGs blended with renewable plant-based materials and reinforced with biopolymers. These products are vegan, melamine-free, dishwasher-safe, and fully compostable, demonstrating the feasibility of integrating SCGs into sustainable product design.

In conclusion, the disposal of spent coffee grounds should not be viewed merely as a waste management challenge but rather as an opportunity for sustainable innovation. The valorization pathways outlined above highlight the versatility and economic potential of SCGs, reinforcing their role as a valuable resource in the global transition toward greener production systems.

3. MATERIALS AND METHODS

The aim of the study was to compare the efficiency of soluble compound extraction from coffee using a specially designed extraction basket (Type II) under three process variants, differentiated by the type of input material and the extraction medium applied. The investigation focused on evaluating the influence of these factors on process dynamics and the changes in the concentration of dissolved substances over time, expressed as TDS (Total Dissolved Solids). The experiments were carried out using a cold maceration method, i.e., at temperatures not exceeding 30 °C – typical for cold brew processes – under conditions of forced, repeated flow of the extraction liquid through the coffee bed. An important objective of the study, with both technological and economic relevance, was to assess the potential for recovering soluble compounds from previously used coffee grounds. The study examined the feasibility of optimizing the cold brew extraction process through a multi-stage extraction approach, which may contribute to more efficient raw material utilization and reduced production costs.

The following extraction variants were applied:

- Test A – classical extraction of fresh coffee in a flow-through system,
- Test B – secondary extraction of previously used coffee grounds with fresh water,
- Test C – extraction of fresh coffee using the extract obtained in Test B.

To verify the results and assess process repeatability, each test was repeated using ground coffee of identical particle size (grind level no. 6), in accordance with the established experimental procedure. The repeated series were denoted as A′, B′, and C′, respectively.

3.1. Materials

The experimental material consisted of roasted Arabica coffee beans from Brazil (Fig. 2), roasted in a Giesen drum roaster (Giesen Coffee Roasters B.V., Ulft, The Netherlands) and supplied by Hard Beans Coffee, based in Opole, Poland. To eliminate variability in raw material properties – such as roast degree, preparation method, or origin – and to ensure consistency and comparability of results, all experiments were carried out using beans from the same production batch.

The coffee used in this study was roasted to the first crack at 210–230 °C for 10–18 minutes, producing a light to medium roast that preserves much of the coffee's origin flavors.

(a) (b)

Figure 2. Coffee beans used in the extraction experiments.

Immediately prior to each measurement, the beans were freshly ground using a Mahlkönig EK 43/1 grinder (Mahlkönig, Hamburg-Wandsbek, Germany), with the grind size set to level 6 on the manufacturer's 12-point scale (Fig. 3a). This setting produced a medium-fine grind, with coffee particles averaging approximately 600 µm. Sieve analysis confirmed that, at this setting, the particle size ranged from 400 to 700 µm.

The mass of coffee grounds and the volume of water used for extraction were 1280 g and 12.2 L, respectively, corresponding to a coffee-to-water ratio of 1:9.5 (i.e., 105 g of coffee per 1 L of extraction liquid) (Fig. 3b).

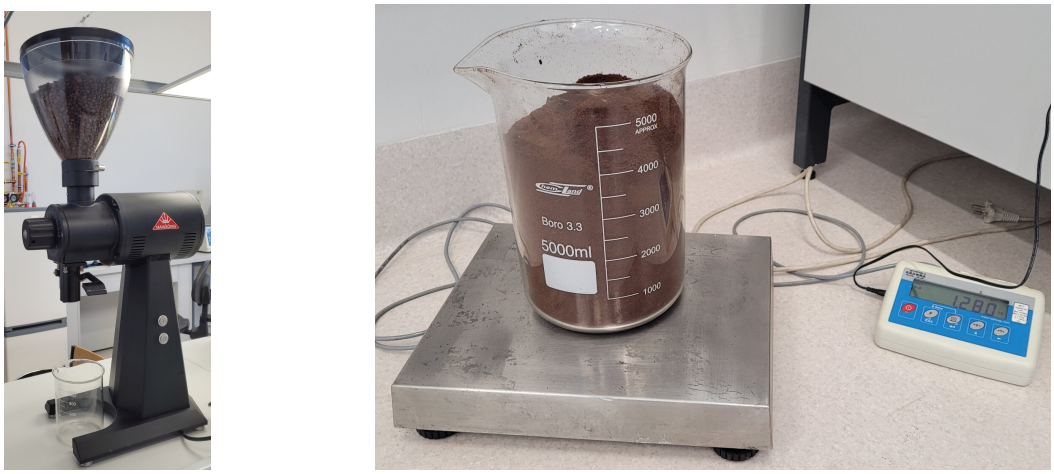
The applied coffee-to-water ratio (1:9.5) falls within the standard range of 1:8–1:10, commonly used for the preparation of high-strength coffee extracts (Rao and Fuller, 2018; Putro et al. 2021). The increased proportion of coffee relative to the liquid phase promotes the production of a concentrate rich in aroma and flavour compounds, which can subsequently be subjected to concentration or stabilization processes.

3.2. Experimental setup

The experimental investigations were carried out using the setup schematically illustrated in Fig. 4. The system consisted of a stainless steel tank with a capacity of 28 L (1), a specially designed extraction basket (2), a pumping system equipped with a liquid flow rate measurement unit, as well as sensors for temperature, pH, and total dissolved solids (TDS).

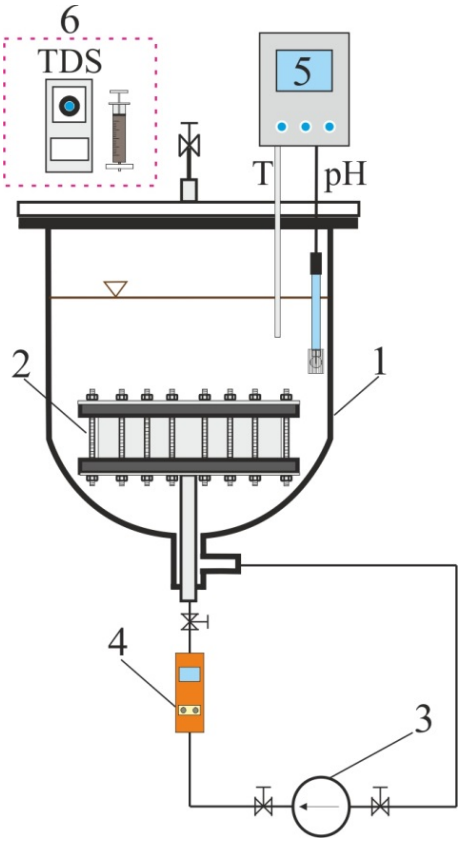
The extraction basket (2), whose characteristic dimensions are shown in Fig. 4, consisted of a bottom closure in the form of a solid stainless-steel plate fitted with an inlet nozzle (d). Above it, a perforated plate was positioned to support the coffee bed and ensure uniform liquid distribution.

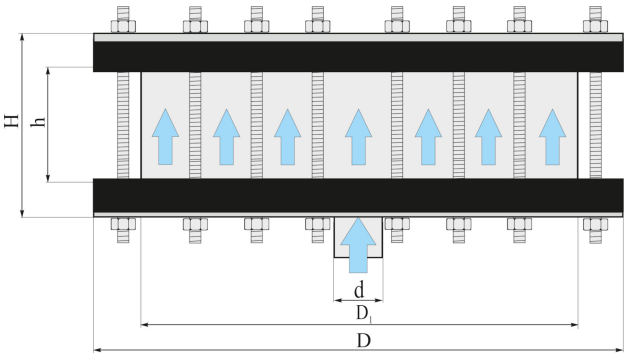
The upper section of the basket featured a reinforced grid cover integrated with a mesh that prevented coffee particles from migrating into the tank. The basket (2) was mounted at the bottom of the tank (1), which was equipped with a centrally installed supply and outlet nozzle for delivering and discharging the extraction liquid.



(a) (b)

Figure 3. Raw material preparation: a) Mahlkönig EK43 grinder with a wide grind size adjustment range; b) ground coffee sample prepared for extraction experiment.





Extraction basket dimensions:
D=264 mm
D_1=260 mm
h=65.0 mm
H=89 mm
m=3855 g

Figure 4. Experimental setup: 1 – tank (V = 28 L), 2 – extraction basket, 3 – pump, 4 – flow meter, 5 – pH and temperature meter, 6 – TDS measurement kit (refractometer, syringe, disposable filters).

The flow of liquid through the bed in a recirculating system was driven by a Pedrollo centrifugal pump (3) with a capacity of up to 150 dm^3/min. The flow rate was measured using a KOBOLD DF-24DR15WMS3S electronic flow meter, with a measurement range up to 24 dm^3/min and an accuracy of ±2.5% of the full scale.

The mass of the material, the empty basket, and the loaded basket were measured using a RADWAG WTC 15/30C1/K laboratory balance with an accuracy of ±5 g. The volume of the extraction liquid was measured using a 5 L beaker and a 100 cm^3 graduated cylinder.

Tap water with physicochemical properties determined based on laboratory analyses was used in the experiments. The results of the water analysis are presented in Table 2.

Table 2. Physicochemical properties of the water used in the study (Basket Type II).

Parameter	Unit	Measured values
Electrical conductivity, κ	µS/cm	410.1–412.1
Total hardness, T_{og}	mg $CaCO_3$/L	160–163
Calcium hardness, T_{Ca}	mg Ca^{2+}/L	48.1
Magnesium hardness, T_{Mg}	mg Mg^{2+}/L	9.72–10.50

The pH and temperature of the extraction liquid during the experiment were measured using a CPC-411 pH/conductivity meter (ELMETRON), with an accuracy of ±0.01 pH and ±0.1 °C, respectively. The total dissolved solids (TDS) content in the coffee extracts was determined using a VST Inc. Coffee Refractometer, which allows rapid measurement in the 0–20% range, with an accuracy of ±0.03%.

3.3. Experimental procedure

The procedure adopted for the experiments (Tests A and C, as well as A′ and C′) involved the preparation of a specified mass of freshly ground coffee (grind level 6) and its placement in the extraction basket. The preparation of the basket followed the steps outlined below:

- grinding the coffee to the required particle size (grind level 6/12),
- determining the mass of the coffee charge and the empty basket with lid fasteners using a RADWAG WTC 15/30C1/K laboratory balance (accuracy ±5 g),
- evenly filling the basket with the weighed portion of ground coffee,
- re-weighing the filled basket including the fastening elements to verify the total mass,
- sealing the basket with the lid and fastening elements to ensure system tightness.

The coffee-filled basket was mounted inside the stainless steel tank (Tests A, A′) and filled with water in a quantity corresponding to the designated coffee-to-water ratio. To replicate industrial conditions – where filling typically occurs from the bottom – and to avoid directly soaking the upper lid of the basket, water was introduced into the tank by flowing it over a steel plate positioned above the extraction basket. The liquid ran down the plate and then along the inner walls of the tank, gradually filling the working chamber from the bottom. This filling method effectively simulated real-world industrial conditions, in which the coffee bed is gradually saturated from below.

Prior to initiating the experiments conducted in a flow-through system with forced circulation of liquid through the coffee bed, the basket containing the coffee was submerged in water for 5 minutes ($t_0 = 5$ min) to allow for initial soaking and deaeration. After this pre-treatment, the pumping system was activated, initiating the circulation of the liquid in a closed-loop configuration. From the moment the pump was turned on, the duration of the extraction process was recorded.

The measurement of total dissolved solids (TDS) was carried out over a 45-minute period, with data recorded at one-minute intervals. At each time point, four replicate TDS measurements were performed using a representative, compositionally averaged sample collected from the tank with syringes. The residual liquid remaining in the syringe after TDS measurement was returned to the tank to avoid altering the liquid-to-solid ratio during the process. After 45 minutes, the pump was turned off, marking the end of the extraction process. The coffee extract was then drained, and the basket was emptied.

The measurement procedure in Test B, referred to as the secondary coffee extraction, involved the reuse of the coffee bed remaining from Test A. After completing the primary extraction, the tank was emptied of extract using a pump, and the basket containing the spent coffee was removed. To eliminate any risk of contamination of the coffee bed and to ensure the reliability of the measurements, the entire system was rinsed with clean water. This step effectively removed residual concentrated extract from the piping and other components of the pumping system. After rinsing, the water was drained from both the tank and the circulation system.

The basket containing the previously extracted coffee (residue from Test A) was reinserted into the extraction tank and filled with fresh water in the same volume as used in Test A, i.e., 12.2 L. From that point onward, the flow parameters and measurement procedures in Test B were identical to those applied in Test A. The same procedure was followed for Test B′.

In Test C, the extraction medium consisted of the extract obtained in Test B, into which a basket filled with freshly ground coffee was immersed. As in the other experimental variants, the coffee bed was pre-soaked for 5 minutes. After this period, the pump was activated, initiating the extraction process. Test C′ was carried out analogously, using the extract obtained in Test B′ as the extraction medium, and applying the same process parameters and measurement methodology.

The experiments were conducted with the liquid temperature ranging from 20.2 °C at the start to a maximum of 29.4 °C after 45 minutes, due to heat generated within the system's pumping circuit. The initial tap water temperature varied between 20.2 and 21.6 °C. Differences between the pre-soaking coffee bed temperature and the maximum temperatures across all variants ranged from 1.7 to 5.9 °C, indicating minor variations, while no actual fluctuations or decreases occurred during the process. The ΔT values, representing the difference between the final extraction temperature T_k and the coffee bed temperature T_o after pre-soaking, reflect the overall temperature increase during the process as the liquid was pumped through the coffee bed. Specific details regarding temperature changes observed during the extraction process are presented in Table 3.

During the experiments, changes in pH were also monitored throughout the extraction process. The results showed a systematic decrease in pH – from approximately 6.4 in the initial minutes to a minimum of 5.4 after 45 minutes of extraction.

To ensure reliability and assess the repeatability of the results, each test (A, B, C) was performed twice as part of two independent experimental series.

Table 3. Initial, pre-soaking, and final extraction temperatures for all tested variants.

Test	Initial temperature of the extraction medium, T [°C], ($t = 0$ min)	Pre-soaking coffee bed temperature, T_o [°C], ($t_o = 5$ min)	Extraction temperature, T_e [°C] ($t_e = 1$ min)	Final extraction temperature, T_k [°C] ($t_k = 45$ min)	$\Delta T = T_k - T_o$, [°C]
A	20.2 (tap water)	22.1	22.3	28.0	5.9
B	21.6 (tap water)	22.3	22.6	28.0	5.7
C	23.9 (extract)	23.9	24.0	29.4	5.5
A′	21.6 (tap water)	22.1	22.1	25.9	3.8
B′	20.2 (tap water)	20.4	21.2	23.5	3.1
C′	21.6 (extract)	21.7	21.7	23.4	1.7

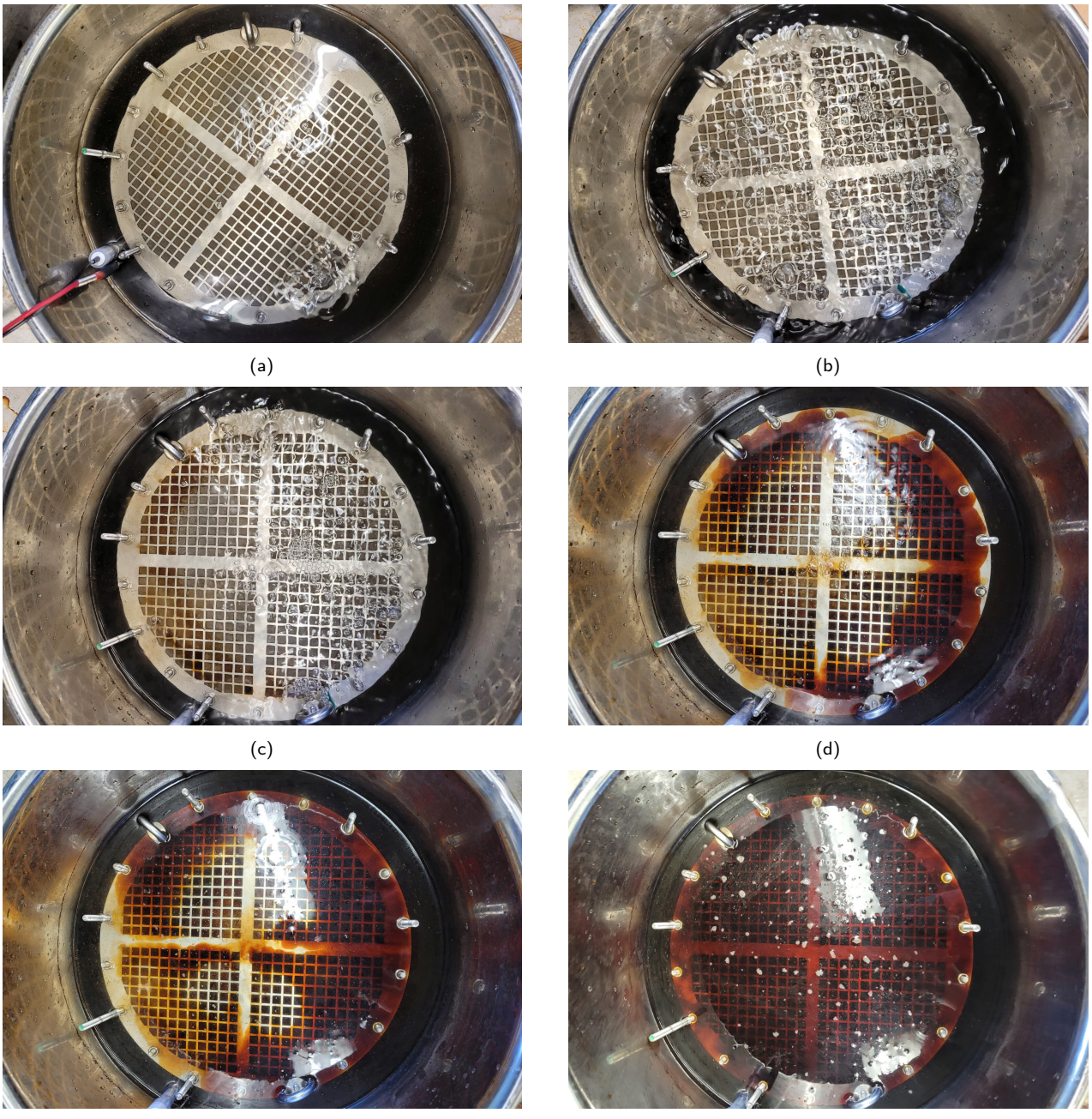
4. RESULTS AND DISCUSSION

The following section presents the results of the experimental study on cold brew coffee extraction, including both qualitative observations and quantitative analyses of total dissolved solids, extraction efficiency, and bioactive compound content. Additionally, the chemical composition, sensory attributes, and microbiological stability of the extracts are discussed to evaluate the effectiveness and reproducibility of the multi-step extraction method.

4.1. Total dissolved solids

The results of the conducted experiments are presented in both qualitative and quantitative terms. The qualitative observations are illustrated in Figures 5 to 8, while the quantitative evaluation of the extraction process is shown in Figure 9.

Figures 5a–f depict the initial minutes of the extraction process in Test A, including the spontaneous release of air bubbles during the soaking stage (Figure 5a), the movement of bubbles in the liquid induced by the operation of the pumping system



(a) (b) (c) (d) (e) (f)

Figure 5. Initial stages of the extraction process – Test A (top view of the tank interior): a) soaking and deaeration of the coffee bed ($t_0 = 5$ min), b) pump activation – displacement of air from the bed, c–f) gradual release of extract ($t \leq 1$ min).

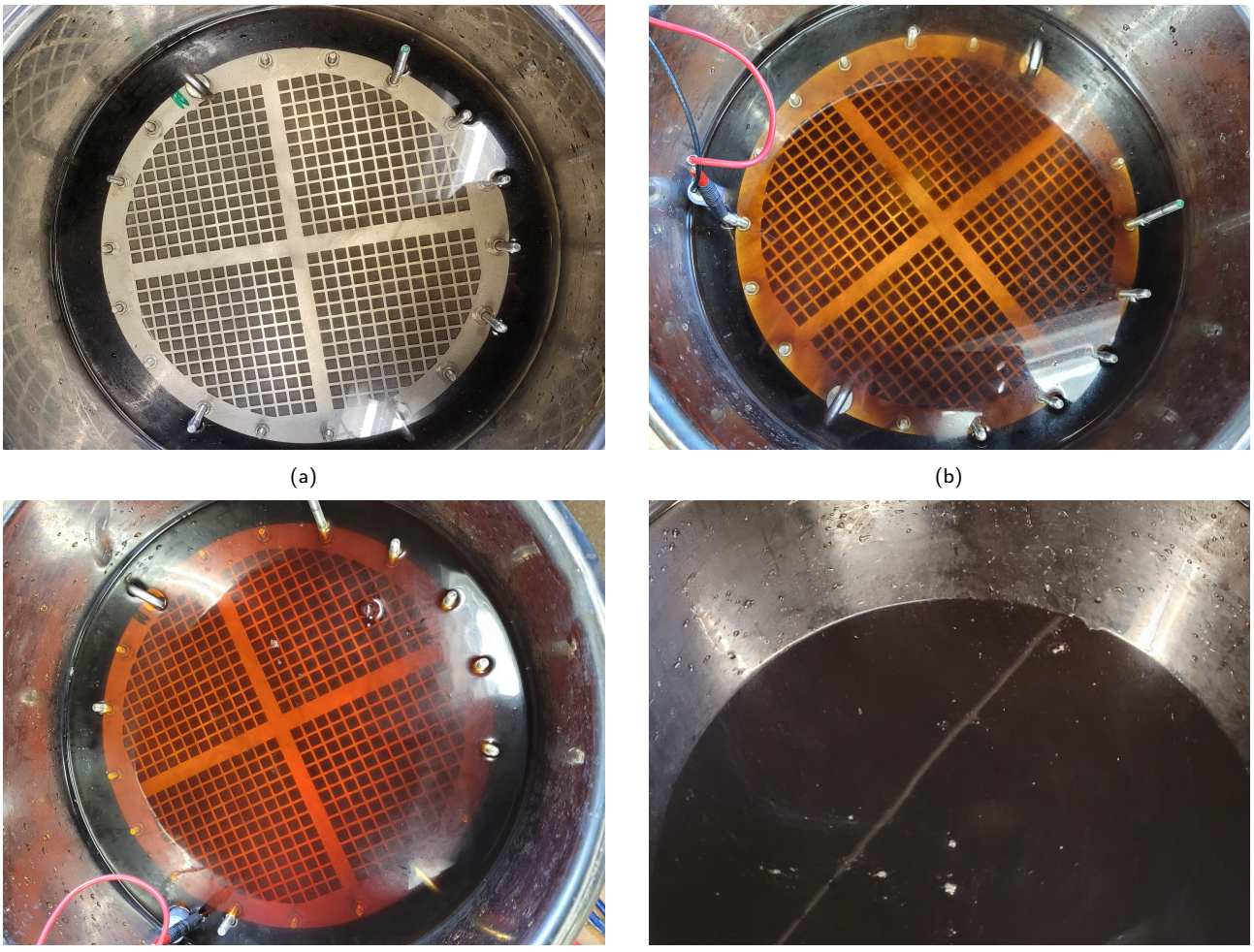
(Figure 5b), and the progression of extraction within the first minute of the experiment (Figures 5c–f). In Figures 5c–f, a visible change in the coloration of the liquid within the extraction basket can be observed, indicating the release of soluble compounds from the coffee bed.

The extraction process in Test B′, conducted as a secondary extraction of a previously used coffee bed with fresh water, is illustrated in Figure 6. The image in Figure 6a shows the Type II basket filled with coffee grounds previously extracted in Test A′, submerged in fresh water during the soaking stage ($t_0 = 5$ min). Figures 6b–c depict the initial stage of liquid flow through the coffee bed immediately after the pumping system was activated ($t \leq 1$ min), while Figure 6d presents the appearance of the extract in the tank at the end of the extraction process, following the removal of the basket ($t = 45$ min).

Figure 7 illustrates the course of the extraction process in Test C. Figure 7a shows the initial soaking stage of the coffee bed, during which a basket filled with freshly ground coffee was immersed in the extract obtained from Test B. In turn, Figure 7b presents the appearance of the extract after completion of the process and removal of the basket from the tank ($t = 45$ min).

To verify the maximum TDS value obtained during the experiment, a sample of the extract was collected for analysis after the process was completed and the basket was removed from the tank (Fig. 8). In each case, the results of this analysis confirmed the maximum TDS measured at the end of the experiment.

In the initial minutes of the process, fluctuations in volumetric flow rate were observed, as indicated by unstable readings on the flowmeter. This phenomenon resulted from bed expansion caused by water absorption – both during the soaking phase and the ongoing extraction – commonly referred to as bed settling. Following this initial period of flow instability, the system stabilized, and the flow rate remained constant, not exceeding 10 L/min.



(a) (b) (c) (d)

Figure 6. Interior view of the tank with type II basket (Test B′): a) basket filled with previously extracted coffee from Test A′ immersed in fresh water ($t_0 = 5$ min), b–c) basket with coffee after activation of the pumping system ($t \leq 1$ min), d) extract in the tank after removal of the coffee basket ($t = 45$ min).

(a) (b)

Figure 7. Interior view of the tank with type II basket (Test C): a) soaking of the basket in the extract from Test B ($t_0 = 5$ min), b) extract after completion of the experiment ($t = 45$ min).

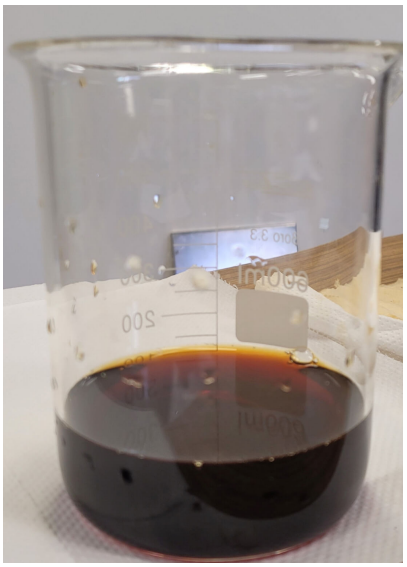


Figure 8. Coffee extract sample collected after the completed process ($t = 45$ min) for verification of the maximum TDS.

The cold brew coffee extraction process (carried out in three variants) was analyzed with respect to the measured values of total dissolved solids (TDS) concentration, as well as changes in key parameters such as extraction yield (EY) and the percentage increase in extraction efficiency (ΔTDS).

Figure 9 presents the interpreted results. Each data point corresponds to the average of four independent measurements on liquid samples collected at one-minute intervals over the 45-minute extraction cycle, giving a total of 180 TDS determinations per series. The comparative analysis of TDS concentration changes over time illustrated in this figure includes both the base tests (A, B, and C) and the comparative tests (A′, B′, and C′). The maximum TDS values obtained across all tests are summarized in Table 4.

Table 4. Comparison of maximum TDS values in baseline and repeat tests.

Test variant	Maximum TDS [%] (Tests A, B, C)	Maximum TDS [%] (Tests A′, B′, C′)	Difference vs. repeat test [%]
Test A and A′	1.95	2.07	+6.15%
Test B and B′	0.62	0.48	–22.58%
Test C and C′	2.65	2.58	–2.64%

For each of the base (A, B, C) and repeated (A′, B′, C′) test variants analyzed, a characteristic pattern of TDS concentration changes over time was observed (Figure 9). In Tests A and A′, involving a single extraction of the coffee bed with fresh water, a stable and consistent increase in total dissolved solids (TDS) concentration was recorded, reaching saturation levels of approximately 1.95% for Test A and 2.07% for Test A′ after about 30 minutes (lines 6 and 5, respectively). The saturation point refers to the moment when the concentration of dissolved substances in the extract no longer changes significantly (within the ±0.03% accuracy of the refractometer), indicating equilibrium between the solid (coffee) and liquid phases. The course of TDS concentration changes in both cases reflects the typical profile of coffee extraction, characterized by an initial, intense phase of leaching soluble compounds from the surface and interstitial spaces of the coffee grounds (rapid TDS increase), followed by a gradual flattening of the curve, indicating the achievement of extraction equilibrium and the depletion of most easily soluble constituents from the raw material.

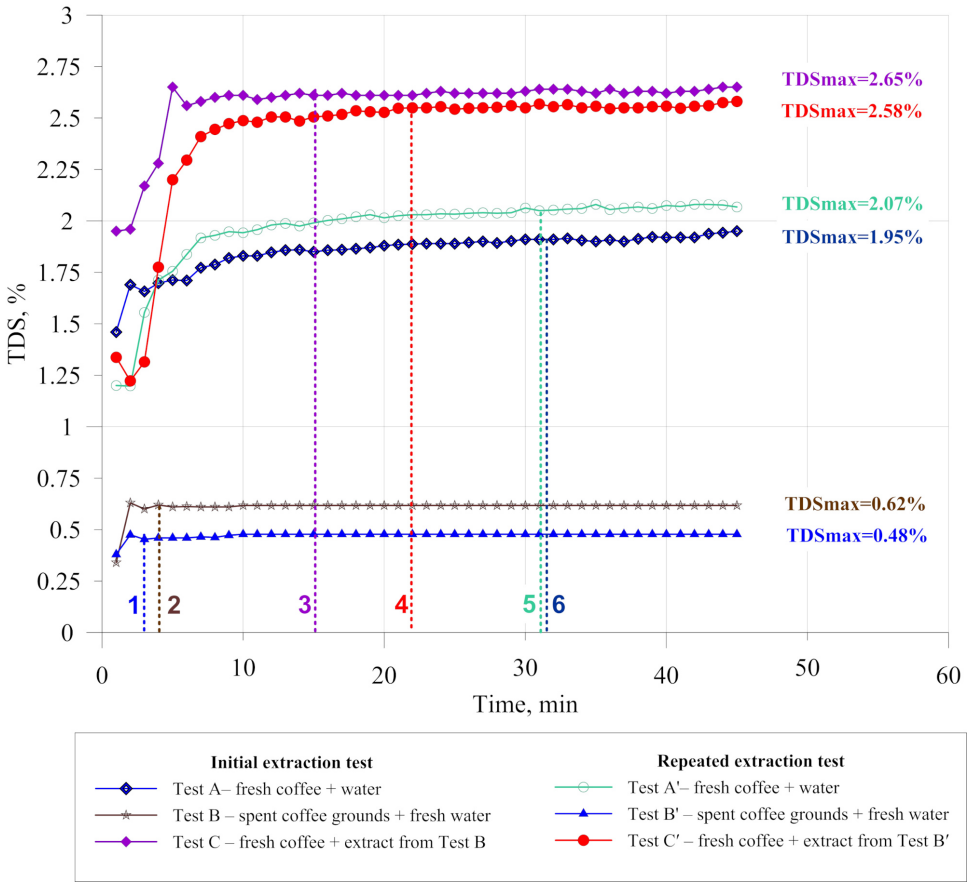


Figure 9. Comparative analysis of TDS variation over time for the initial extraction tests (A, B, C) and repeated extraction tests (A′, B′, C′).

Tests B and B′, which involved secondary extraction of previously used coffee grounds with fresh water, demonstrated significantly lower TDS values compared to primary extraction. In Test B, the maximum concentration of dissolved solids reached approximately 0.62%, with solution saturation occurring as early as the 4th minute (line 2). In Test B′, the TDS value was even lower – reaching a maximum of 0.48%, with the curve stabilizing after about 3 minutes (line 1). Analysis of subsequent measurement points indicates that TDS variation remained within the refractometer's margin of error (±0.03%), and no further significant increases in TDS were observed. The shape of both curves reflects the rapid release of residual soluble compounds from the coffee, confirming the limited extractive potential of the spent grounds. These results suggest that the duration of secondary extraction can be effectively reduced to just a few minutes (3–4 min) without significant loss in efficiency. This approach allows for substantial reductions in energy use and processing time, which, on an industrial scale, could directly lower operational costs and improve technological throughput.

The noticeable large difference in initial TDS values between Tests A and B can be attributed to the soluble compound content of the coffee bed. Test A, with a fresh bed, exhibited a relatively high initial TDS of approximately 1.5%, with a rapid release of compounds during the first minute, as shown in photos of the tank interior (Fig. 5). In contrast, Test B started with a much lower TDS (0.34%) due to the use of spent, previously extracted and drained coffee bed, through which clean water was pumped, resulting in a less concentrated extract (see Fig. 6 for Test B′, the repeat of Test B under the same conditions).

Test C and its corresponding counterpart (C′), using extract from tests B and B′ respectively as the extraction medium for fresh coffee grounds, exhibited the highest TDS values among all analyzed variants. In Test C, the TDS value reached approximately 2.65%, with saturation achieved after 15 minutes (line no. 3). In Test C′, a rapid increase in dissolved solids concentration was observed during the first 20 minutes, with a maximum value of 2.58% and saturation reached after 22 minutes (line no. 4). The results confirm the synergistic effect of using a previously enriched extraction medium in combination with fresh coffee material.

The analysis of final TDS values (summarized in Table 4) enabled the assessment of extraction process repeatability by comparing the baseline tests (A, B, C) and their corresponding counterparts (A′, B′, C′). In the case of tests A and A′, the difference in TDS values was ±6.15%, which falls within the typical variability range of process parameters. Tests C and C′, on the other hand, showed only a minimal difference

(±2.64%), which confirms good repeatability, comparability of results, and stability of the process in both cases. The obtained results may also indicate the existence of a saturation threshold of the extract under conditions of repeated forced liquid flow through the coffee bed. In contrast, tests B and B′ – representing secondary extraction of previously exhausted coffee grounds – showed a significantly greater difference in maximum TDS values, reaching ±22.58%. One possible explanation for the noticeable reduction in dissolved solids content (TDS) during the second extraction cycle (Test B′) may be the partial gravitational draining of the liquid from the coffee bed when transitioning from Test A to Test B. The loss of extract rich in dissolved substances, particularly from intergranular spaces, could have substantially diminished the extraction potential of the subsequent flow, as a significant portion of soluble compounds is released not only from the interior of the ground coffee particles but also from the spaces between them.

The analysis of the data summarized in Table 5 indicates that secondary extraction enables the recovery of a significant amount of soluble compounds from coffee grounds previously subjected to primary extraction.

Table 5. Comparison of primary and secondary extraction efficiency.

Extraction variant	Max. TDS [%]	TDS recovery relative to primary extraction [%]
A (primary)	1.95	–
B (secondary)	0.62	31.8%
A′ (primary)	2.07	–
B′ (secondary)	0.48	23.1%

The recovered TDS amounted to 31.8% and 23.1% of the baseline TDS values obtained during primary extraction for variants B and B′, respectively. The experimental results also demonstrate a considerably shorter extraction time and thus a faster saturation of the liquid with soluble substances – up to 30 minutes for primary extraction under forced flow conditions and only 3–4 minutes for secondary extraction. This suggests that the sensory properties of the brew are unlikely to deteriorate compared to those of a traditional 24-hour cold brew process, as also confirmed by the findings of Stanek et al. (2021).

It is worth noting that coffee grounds after primary extraction are typically treated as waste. The possibility of their reuse in a secondary extraction process highlights a significant potential for improving the efficiency of compound recovery and reducing raw material losses.

For the purposes of quantitative process evaluation, extraction yield (EY), expressed as a percentage, was employed as a comparative indicator of extraction efficiency across the various experimental conditions. This metric quantifies the fraction of the dry mass of the raw material (coffee) that underwent solubilization and was subsequently transferred into the liquid phase during the low-temperature cold brew extraction process. The extraction yield (EY) is defined by Eq. (1).

$$\mathrm{EY} = \frac{\mathrm{TDS} \cdot m_E}{m_c} = \frac{\mathrm{TDS} \cdot V_E \cdot \rho_E}{m_c}$$
$$\Delta p = \frac{2\sigma}{R_x} = \gamma \left(\frac{1}{a} - \frac{1}{b} \right) \quad (1)$$

where: EY – extraction yield,%; TDS – total dissolved solids in the extract,%; m_E – mass of the extract, g; V_E – volume of the extract, ml, ρ_E – density of the extract, g/ml; m_E – dry mass of the coffee sample, g.

The EY values for the conducted tests were calculated based on an experimentally determined average density of the coffee extract, measured using the pycnometric method and assumed to be 1030 kg/m^3. These data for each experimental series are presented in Table 6.

As shown in Table 6, the reference tests A and A′ yielded extraction yields (EY) of 19.14% and 20.42%, respectively, which fall within the typical range for effective cold brew extraction of fresh coffee (18–22%). In contrast, tests B and B′ (representing secondary extraction of the same coffee bed) produced significantly lower EY values – approximately 6% and slightly below 5%, respectively.

This indicates that the majority of soluble compounds had already been extracted during the first extraction cycle, and only a small fraction remained available for dissolution during the secondary flow of the extraction liquid.

The highest EY values were observed in tests C and C′ – 26% and 25%, respectively. These results suggest that using a previously enriched extract as the working fluid considerably enhances the extraction capacity of the system. This is likely due to facilitated dissolution of the active compounds and more efficient mass transfer into the solvent.

A comparison of extraction efficiency, expressed as the TDS value per unit mass of coffee (Y_{TDS}) as well as the percentage increase in TDS for tests C and C′ relative to the baseline tests A and A′, is presented in Table 7. The use of previously obtained extract instead of fresh water significantly enhanced the extraction efficiency of dissolved substances (TDS) – in both cases (tests C and C′), a notable increase in yield parameters was observed.

The percentage increase in extraction efficiency (ΔTDS) was calculated according to Eq. (2).

$$\Delta\mathrm{TDS} = \frac{\mathrm{TDS}_{(\mathrm{Test}\ P)} - \mathrm{TDS}_{(\mathrm{Test}\ K)}}{\mathrm{TDS}_{(\mathrm{Test}\ K)}} \cdot 100\%$$
$$\Delta p = \frac{2\sigma}{R_x} = \gamma \left(\frac{1}{a} - \frac{1}{b} \right) \quad (2)$$

Table 6. Comparison of TDS yield efficiency in the analyzed tests.

Test variant	Water volume [dm^3]	Maximum TDS [%]	Coffee mass, m_c [g]	Mass of dissolved solids, m_s [g]*	Extraction yield $Y = m_s/m_k$ [g/g coffee]	EY [%]
Test A	12.2	1.95	1280	245.04	0.1914	19.14
Test B		0.62		77.91	0.0609	6.09
Test C		2.65		333.00	0.2601	26.01
Test A′		2.08		261.37	0.2042	20.42
Test B′		0.48		60.32	0.0471	4.71
Test C′		2.58		324.13	0.2532	25.32

* – calculated based on an assumed extract density of $\rho_E = 1030$ kg/m^3

where: ΔTDS – percentage increase in TDS-based extraction efficiency relative to the classical method [%]; $TDS_{Test\,P}$ – TDS value obtained in the extraction test of fresh coffee using previously enriched extract (tests C and C′),%/g; $TDS_{Test\,K}$ – TDS value obtained in the reference extraction test of fresh coffee using pure water (tests A and A′),%/g.

The index Y_{TDS}, presented in Table 7 and expressed in percent per gram of coffee, was used to compare the extraction efficiency across the experimental variants under equal raw material mass conditions. Essentially, this index enables performance comparisons independent of the quantity of input material and indicates the proportion of dissolved solids extracted per gram of coffee. Higher Y_{TDS} values correspond to more efficient utilization of the raw material.

Table 7. TDS yield efficiency across experimental variants.

Test variant	m_c [g]	TDS [%]	Y_{TDS} [%/g]	ΔTDS [%]
Test A	1280	1.95	0.00152	36.2
Test C		2.65	0.00207	
Test A′		2.08	0.00163	23.93
Test C′		2.58	0.00202	

In the analyzed variants, tests C (0.00207 %/g) and C′ (0.00202 %/g) achieved noticeably higher Y_{TDS} values compared to the reference tests A (0.00152 %/g) and A′ (0.00163 %/g). This clearly demonstrates the advantage of using an enriched extract as the working liquid, which enhances extraction efficiency per unit mass of coffee.

For test C, the efficiency increase amounted to 36.2% relative to conventional water-based extraction (test A), indicating a high potential of the pre-enriched extraction medium. In the case of test C′, an increase in ΔTDS of 23.93% was recorded relative to test A′, also confirming an improvement in extraction intensity, albeit to a slightly lesser extent.

The difference in ΔTDS values observed between tests C and C′ may result from the natural variability of the process or from documented differences in the composition of the base extract (originating from tests B and B′). These results clearly confirm that reusing previously obtained extract can significantly improve process economics and enhance extraction efficiency without increasing raw material consumption.

4.2. Extract composition and its stability during multistage extraction

The chemical composition and bioactivity of coffee extracts depend on multiple factors, including origin, processing, and extraction method, which significantly influence the quantity and proportions of bioactive compounds in the resulting extract. The aim of the present study was to determine the content of key components, such as caffeine, chlorogenic acids, and other polyphenolic compounds, in cold brew obtained by multi-step extraction, in comparison with extracts obtained using other methods reported in the literature.

The chemical profiling was performed using High-Performance Liquid Chromatography (HPLC), a robust and widely accepted analytical technique for the quantification of bioactive compounds in complex matrices such as coffee. All chromatographic analyses were conducted at the Łukasiewicz Research Network – Institute of Heavy Organic Synthesis "Blachownia" (Kędzierzyn-Koźle, Poland), under commission from Hard Beans Coffee. The instrumentation comprised a Dionex UltiMate 3000 system, equipped with an automatic pump, injector, autosampler, column compartment, and a UV–Vis detector with photodiode array (PDA) technology. Data acquisition and processing were performed using Chromeleon 6.8 software, ensuring high analytical precision and reproducibility. Quantitative analysis revealed the presence of key alkaloids and polyphenolic acids in substantial concentrations. Specifically, caffeine and trigonelline were quantified at 730 ± 12 mg/100 g and 573 ± 6 mg/100 g of extract, respectively. Among the chlorogenic acids, the following regioisomers were identified and quantified: 3–O–caffeoylquinic acid (3–CQA) – 711 ± 3 mg/100 g, 4–O–caffeoylquinic acid (4–CQA) – 284 ± 2 mg/100 g, and 5–O–caffeoylquinic acid (5–CQA) – 235 ± 1 mg/100 g.

In addition to targeted compound quantification, the global antioxidant potential of the extracts was assessed. The Total Phenolic Content (TPC) of the analyzed extract was measured at approximately 20 mg gallic acid equivalents (GAE)/g, while the Total Flavonoid Content (TFC) reached 3.2 mg quercetin equivalents (QE)/g. Antioxidant activity was evaluated using the two complementary assays – DPPH (2,2-diphenyl-1-picrylhydrazyl) and ABTS (2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)), – yielding radical scavenging capacities of 46 mg Trolox equivalents (TE)/g and 32 mg TE/g, respectively.

These findings are consistent with and extend findings reported by Stanek et al. (2021), who examined Arabica coffees from Guatemala, El Salvador, and Brazil subjected to different post-harvest processing methods (washed, natural, and pulped natural). Their study demonstrated that both coffee origin and processing technique significantly influenced the concentration of key bioactive compounds in the extracts. Notably, coffees extracted via the Hardtank method (forced percolation of the extraction liquid through the coffee bed) exhibited elevated levels of 3–O–caffeoylquinic acid (711–897 mg/100 g) and caffeine (643–795 mg/100 g) with TPC values ranging from 19.86 to 33.46 mg GAE/g, TFC from 2.87 to 4.08 mg QE/g, and antioxidant activities from 33.73–55.52 mg TE/g (DPPH) and 27.63–57.45 mg TE/g (ABTS). Furthermore, the findings compare favorably with those of Maksimowski et al. (2023), who investigated cold brew infusions prepared under controlled temperature and via ultrasound-assisted extraction (UAC). In the study by Maksimowski et al. (2023), the caffeine content in cold brew infusions prepared at 4 °C and 10 °C for 12 h was 0.6 mg/mL, while for the ultra-sound assisted cold brew (UAC), the concentration was 0.56 mg/mL. In the case of trigonelline, the values were 0.5 mg/mL, 0.31 mg/mL, and 0.42 mg/mL, respectively. In this study, coffee extracts obtained using a multi-step extraction in a basket Type II exhibited significantly higher concentrations of caffeine (730±12 mg/100 g of product) and trigonelline (573 ± 6 mg/100 g of product). When normalized to infusion concentrations using a standard coffee-to-water ratio (1:10–1:15), the extract data correspond to approximately 0.56–0.80 mg/mL for caffeine and 0.44–0.57 mg/mL for trigonelline, indicating that the multi-step basket Type II extraction method yields comparably high, if not superior, concentrations of these bioactive compounds.

In this study, not only the composition but also the stability of bioactive compounds was analyzed during the reuse of the extract in multi-step cold brew production. Although direct testing across successive extraction cycles was not performed, literature data and process-based insights support the preservation of the chemical integrity of the bioactive constituents under the applied conditions.

The extraction protocol employed in the study was based on a three-stage cold brew process completed within 60 minutes, significantly shorter than conventional 24-hour maceration. The process was conducted at low temperatures (not exceeding 30 °C) in sealed, light-protected vessels, thereby minimizing exposure to oxygen and photodegradation. These conditions are known to preserve thermolabile and oxidation-sensitive compounds, particularly polyphenols, alkaloids, and diterpenes. Literature data (Farah and de Paula Lima, 2019; Herawati et al., 2024; Maksimowski et al., 2023; Stanek et al., 2021) indicate that key compounds, such as caffeine and chlorogenic acids, are highly stable under the mild, low-temperature conditions characteristic of the cold brew process, which avoids thermal treatment.

Stanek et al. (2021) showed that cold brew prepared using the Hardtank device – based on forced percolation through the coffee bed – can efficiently extract key bioactives, including 3-CQA, caffeine, trigonelline, gallic acid, and 5-(hydroxymethyl)furfural, within just 30 minutes, achieving results comparable to or exceeding those of traditional 24-hour maceration or hot brewing. Notably, the raw material used in the study originated from the same roastery as that used in the present work, ensuring compositional comparability. High-Performance Liquid Chromatography (HPLC) and Fourier Transform Infrared Spectroscopy (FTIR) analyses conducted by Stanek et al. (2021) demonstrated that combining a shorter extraction time with forced liquid flow through the coffee bed in Hardtank minimizes bioactive compound degradation while preserving high concentrations and exhibited elevated lipid content relative to traditional cold and hot brews. These lipids, including cafestol and kahweol, contribute to the sensory and oxidative stability of the beverage. Sensory evaluations confirmed that the shortened extraction time did not compromise organoleptic properties and, in fact, enhanced antioxidant activity.

Herawati et al. (2024) reported that under ambient storage conditions over 8 weeks, degradation of total phenolic content (TPC) and 5–CQA was limited to 11% and 19%, respectively, with tannin loss at approximately 10%.

In this study, the extraction process was completed within 60 minutes, and the extract was either used immediately or stored under refrigerated conditions (5 °C, sealed, protected from light) for no longer than 5 days. Therefore, it is reasonable to infer that degradation of bioactive compounds during the reuse of the extract in the subsequent extraction step was negligible. Furthermore, in the context of ready-to-drink (RTD) coffee, studies by Soares et al. (2025), Bellumori et al. (2021), and Kazes et al. (2024) indicate that long-term storage and stabilization treatments (e.g., pasteurization, high-pressure processing) can induce physicochemical changes affecting sensory properties such as increased acidity, aroma loss, and off-flavor development. However, these effects are not relevant to the present study, which focuses on freshly prepared cold brew intended for short-term consumption (recommended storage: up to 3 days at 4 °C). Sediment formation (due to incomplete filtration), primarily composed of polysaccharides (e.g., galactomannan, arabinogalactan), proteins, and lipids, may occur but is minimal and does not adversely affect sensory quality (Delgado et al., 2008).

In summary, although direct stability testing across extraction cycles was not performed, the mild extraction conditions, short processing time (60 min), and protective storage environment strongly support the chemical integrity of the bioactive compounds in the obtained extract. The extraction mechanism – analogous to the patented Hardtank system – ensures minimal degradation and high retention of functional constituents, thereby enabling effective reuse of the extract for fresh coffee bean processing without compromising biochemical or sensory quality.

4.3. Sensory properties of the cold brew extracts

Sensory analysis is a critical component in assessing beverage quality, particularly for specialty coffee, where flavor, aroma, and mouthfeel are key determinants of consumer acceptance and product classification (Liang et al., 2024). In this study, the sensory evaluation was carried out following the internationally recognized Coffee Cupping Protocol developed by the Specialty Coffee Association (SCA), which includes ten core attributes: aroma, flavor, aftertaste, acidity, body, balance, uniformity, clean cup, sweetness, and overall impression. Coffees scoring ≥ 80 points are classified as specialty grade, reflecting their superior sensory and chemical profiles, as well as their origin and overall high quality. At Hard Beans Coffee – the supplier of the coffee used in this study – sensory evaluation is routinely performed upon delivery of green coffee samples sourced globally. A panel of five certified Q-graders conducts two independent cupping sessions using the SCA scoring system. For hot brew evaluation, green beans are roasted 48 hours prior to cupping following origin-specific roasting curves. Samples are ground no later than 15 minutes before brewing, and hot water (97 °C) is poured directly over the coffee dose. After a 4-minute steeping period, sensory assessment begins (Zarebska et al., 2022).

For cold brew evaluation, sensory analysis is conducted at multiple stages of the extraction process, particularly when working with newly sourced beans or optimizing extraction parameters. During production, samples are collected at defined intervals from the extraction tank (eight cups per sampling point) to monitor flavor development. The first sampling occurs $\sim$ 20 minutes after extraction begins, allowing assessment of the beverage's latent sensory potential. Following the preliminary evaluation, the extraction continues up to 40–60 minutes, after which a second round of sensory analysis is conducted. If the sensory attributes meet predefined quality thresholds – particularly those linked to origin-specific flavor notes – the extraction is terminated to preserve the desired profile.

For coffees with a previously defined sensory profile (established through standard cupping and linked to plantation location), the sensory panel may be conducted only after the designated extraction time for that production batch.

Post-extraction, the cold brew is stored for 1 hour at 4 °C to allow equilibration of volatile compounds and sedimentation of suspended particles. This resting period enhances aroma integration and flavor balance. The beverage is then re-evaluated by the sensory panel. Under refrigerated conditions (4 °C), the final product remains stable for up to 3 days without perceptible changes in sensory quality.

The sensory analysis of the Brazilian-origin coffee used in this study yielded a total score of 83 points, classifying it as specialty coffee. The beverage exhibited bright acidity, layered flavor complexity, and a clean, persistent aftertaste. Across all evaluated attributes – including aroma, flavor, aftertaste, acidity, balance, and overall impression – the samples demonstrated high sensory integrity and alignment with origin-specific descriptors (Table 8). These findings are consistent with the study by Stanek et al. (2021), in which traditional cold brews, hot brews, and percolated cold brews were analyzed and compared using the Hardtank method with coffees from various geographical origins, including Brazil. Their study demonstrated that percolated cold brews – achieved through repeated forced liquid flow through the coffee bed – exhibited sensory scores comparable to hot brews and superior to traditional 24-hour maceration. The study also showed that many of the analyzed sensory attributes received higher scores when maceration and percolation of the coffee bed were applied, compared to traditional hot brewing. Notably, shortening the extraction time to 30 minutes while maintaining percolation dynamics resulted in enhanced aroma, flavor, and balance, supporting the sensory potential of rapid cold brew techniques.

Table 8. Sensory evaluation of cold brew coffee extract (Brazilian Origin) according to SCA Protocol.

Sensory attribute	Score (0–10)	Description
Aroma	8.25	Intense, sweet, with notes of roasted nuts and cocoa
Flavor	8.50	Complex, balanced, with hints of caramel, citrus, and dried fruit
Aftertaste	8.00	Clean, persistent, slightly fruity
Acidity	8.25	Bright, citric, well-integrated
Body	7.75	Medium, smooth, with velvety texture
Balance	8.00	Harmonious integration of flavor, acidity, and body
Uniformity	10.00	Consistent across all cups
Clean Cup	10.00	No off-flavors or defects detected
Sweetness	8.25	Natural sweetness, well-pronounced
Overall Impression	8.50	High-quality beverage with origin-reflective character

Notes: Evaluation conducted by a panel of five certified Q-graders. Protocol based on Specialty Coffee Association (SCA) standards. Cold brew prepared using a three-stage extraction (60 min, ≤ 30 °C). Final product stored 1 hour at 4 °C prior to evaluation.

4.4. Microbiological stability of the CB extracts

Cold brew coffee, due to its minimal degree of processing and absence of thermal treatment, is inherently susceptible to microbial proliferation. The microbiological stability of such products is primarily determined by the hygienic integrity of the production environment, the quality of raw materials, and post-extraction storage conditions. Particular attention must be paid to minimizing contamination from airborne microorganisms and biofilm-forming species within the technological system. The use of food-grade disinfectants and aseptic handling protocols is essential to mitigate these risks.

As highlighted by Zarebska et al. (2022), the freshness and proper storage of green coffee beans are critical for preserving both chemical integrity and sensory quality. Improper storage of green coffee beans can lead to degradation of key bioactive compounds and a flattening of the beverage's flavor profile. Furthermore, Amiri et al. (2024) emphasize the potential contamination of coffee products with ochratoxin A (OTA), a mycotoxin produced by *Aspergillus* and *Penicillium* species. OTA poses significant health risks due to its nephrotoxic, immunosuppressive, and carcinogenic properties. In addition, microbial metabolism during storage may lead to the formation of biogenic amines (e.g., putrescine, tyramine, histamine), which are associated with foodborne intoxications and allergic reactions. The roasting process itself can also contribute to the formation of furan, a pyrolytic compound recognized as a potential human carcinogen.

Overall, these findings emphasize that both microbial contamination and chemical transformations occurring during storage and roasting significantly affect the microbiological stability, safety, and sensory quality of coffee.

The microbiological stability of the CB extracts was evaluated through comprehensive analyses at the Institute of Biotechnology, Opole University (Poland). The testing protocol included quantification of total mesophilic aerobic bacteria, yeasts and molds, coliforms, *Escherichia coli*, Enterobacteriaceae (including *Salmonella spp.*), and coagulase-positive *Staphylococcus aureus*. Mold identification was performed using molecular techniques (DNA isolation, PCR amplification, sequencing), while yeast-like fungi were characterized via biochemical profiling using ID 32C tests (BioMérieux).

Averaged coffee samples were collected immediately post-extraction and stored in sterile Simax glass containers under two conditions: refrigerated (5 °C) and ambient (25 °C). Initial bacterial counts were low (324 Colony Forming Units (CFU)/mL), with no fungal presence detected. After seven days at 5 °C, mesophilic bacteria increased to 3.9×10^4 CFU/mL, and fungi reached 1.0×10^2 CFU/mL. Samples stored at 25 °C exhibited rapid microbial growth, with *Rhodotorula mucilaginosa* reaching 3.2×10^3 CFU/mL within five days, and *Penicillium crustosum* also detected. Importantly, no *Enterobacteriaceae*, *Salmonella* spp., *E. coli*, or *Staphylococcus aureus* were identified in any sample, indicating compliance with European Union food safety standards (Commission Regulation (EC) No 1441/2007). The microbiological stability of the cold brew coffee extract under various storage conditions is presented in Table 9.

In the absence of specific microbiological criteria for cold brew beverages, reference thresholds established for non-pasteurized ready-to-drink products, such as unpasteurized fruit juices, were adopted. These include the absence of *Salmonella* in 25 g of product and acceptable *E. coli* counts between 100 and 1,000 CFU/mL. The results indicate that, under hygienic production conditions and refrigerated storage (5 °C), cold brew coffee remains microbiologically safe for up to five days. When stored at ambient temperature, the shelf life decreases to approximately two days due to accelerated microbial growth. Sensory evaluation conducted during the first three days of refrigerated storage revealed no perceptible changes in aroma,

Table 9. Microbiological stability of cold brew coffee extract under different storage conditions.

Microbiological parameter	Immediately after extraction	After 7 Days at 5 °C	After 5 Days at 25 °C
Total mesophilic bacteria (CFU/mL)	324	3.9×10^4	$> 10^5$
Yeasts (CFU/mL)	Not detected	1.0×10^2	3.2×10^5 (*R. mucilaginosa*)
Molds (CFU/mL)	Not detected	Detected (low level)	Detected (*P. crustosum*)
Coliform bacteria	Not detected	Not detected	Not detected
Escherichia coli	Not detected	Not detected	Not detected
Enterobacteriaceae (including *Salmonella*)	Not detected	Not detected	Not detected
Coagulase-positive *Staphylococcus aureus*	Not detected	Not detected	Not detected

flavor, or mouthfeel. However, extended storage beyond this period led to gradual sensory deterioration, consistent with microbial activity and chemical transformations.

To enhance microbiological safety and extend shelf life, pasteurization is widely employed in commercial cold brew production. This process effectively reduces microbial populations, minimizing the risks associated with the natural susceptibility of cold brew infusions to contamination. Soares et al. (2025) demonstrated that pasteurization at 90 °C for 30 seconds, combined with ultra-clean filling and refrigerated storage (4 °C, dark conditions), maintained microbial counts below 1 log CFU/mL for 150 days. Maksimowski et al. (2023) further confirmed that pasteurized cold brew remained microbiologically stable for up to 270 days at 25 °C, with no detection of *Salmonella spp.*, *E. coli*, or *Listeria monocytogenes*. These outcomes reflect the synergistic effect of thermal inactivation, aseptic packaging, and controlled storage. Moreover, endogenous compounds such as caffeine and chlorogenic acids possess antimicrobial properties, as noted by Farah and de Paula Lima (2019), further contributing to the microbiological resilience of coffee beverages.

In conclusion, the findings indicate that cold brew coffee extracts produced under hygienic conditions and stored appropriately exhibit satisfactory microbiological stability for short-term consumption. For extended shelf life and large-scale distribution, the application of pasteurization or equivalent stabilization methods is recommended to ensure product safety and quality.

5. CONCLUSIONS

To contextualize the results, the present study demonstrates the effectiveness and advantages of a multi-stage cold brew extraction system. Compared to conventional cold brewing, ultrasound-assisted (UAE), and ultra-high pressure (UHP) techniques – which either require long extraction times or yield lower total dissolved solids (TDS) – the multi-stage system consistently achieved 2.65% TDS in just 60 minutes under ambient conditions. Rao et al. (2020) reported TDS values of 1.88–2.06% after 7 hours of cold brewing, Zakaria et al. (2023) reached 2.3% TDS after 15.5 hours, and Córdoba et al. (2019) obtained 0.71–2.04% TDS over 14–22 hours. Ultrasound-assisted extraction achieved 1.43–1.64% TDS within 1 hour (Maksimowski et al., 2023), while countercurrent UAE reached 1.63% in 50 minutes (Liu et al., 2024). UHP extraction yielded only 1.22–1.24% TDS despite high pressures (Chen et al., 2023). In comparison, the multi-stage system not only achieved higher TDS in a shorter time but also preserved the characteristic sensory profile, with dissolved solids content per gram of coffee approximately 6% higher than Córdoba et al. (2019) and 62.6% higher than Liu et al. (2024), indicating superior solute transfer dynamics and extraction efficiency.

The experimental studies conducted in this work compared the extraction efficiency of soluble compounds across three process variants differing in feed composition and extraction medium, all performed under repeated forced liquid flow in a low-temperature cold brew system. The results provide a comprehensive assessment of process effectiveness and support the following conclusions:

- The temporal changes in TDS reflect the classical coffee extraction profile: an initial rapid release of solubles followed by a gradual approach to saturation.
- Process stability is confirmed by the minimal differences in TDS between tests A/A′ and C/C′. Greater variability in secondary extraction tests B/B′ (22.58%) may be attributed to technical factors such as residual drainage from the coffee bed.
- Extraction yield (EY) for fresh-water-based tests (A and A′) falls within the typical cold brew range (18–22%), while tests C and C′, using pre-enriched extract, achieved the highest EY values (26% and 25%, respectively), characteristic of coffee concentrates.
- The use of enriched extract as the working medium significantly increased extraction efficiency, with ΔTDS of 36.2% (C vs A) and 23.93% (C′ vs A′), confirming the advantages of multistage extraction.
- Secondary extraction can be performed in just 3–4 minutes without loss of efficiency, reducing energy consumption and increasing technological throughput.
- The total duration of the multi-stage process ($\sim$ 60 min) is considerably shorter than conventional 24-hour cold maceration and does not compromise sensory quality; the shorter extraction period also limits the release of undesirable bitter compounds.
- Each extraction variant produces a beverage with a distinct chemical and sensory profile. Integrating analytical chemistry, sensory evaluation, and consumer research is essential for determining optimal technical and market performance.

Future studies should focus on optimizing multi-stage extraction parameters to further improve TDS yield, evaluate energy efficiency and environmental impact, and compare the system to non-conventional techniques such as UAE, MAE, and UHP in terms of chemical composition, bioactive and volatile profiling, and sensory quality. Additionally, research on storage stability – including physicochemical, microbial, and sensory changes over time – and consumer acceptance studies across diverse populations will be essential to support sustainable and high-quality cold brew production.

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SYMBOLS

D	external diameter of the basket mounting plate, mm
D_1	diameter of the coffee basket, mm
d	diameter of the liquid inlet nozzle, mm
EY	extraction yield,%
H	total height of the basket, mm
h	height of the retaining ring for the coffee bed, mm
m	mass, g
pH	acidity/alkalinity of extraction liquid, –
t	time, min
T	temperature, °C
TDS	Total Dissolved Solids
ΔTDS	percentage increase in TDS-based extraction efficiency relative to the classical method,%
T_{Ca}	calcium hardness of water, mg Ca^{2+}/L
T_{Mg}	magnesium hardness of water, mg Mg^{2+}/L
T_{og}	total hardness of water, mg $CaCO_3$/L
V	volume, mL
Y	extraction yield efficiency based on TDS, %/g

Greek symbols

κ	electrical conductivity, µS/cm
ρ	density, g/mL

Superscripts

$'$	repeated test (A′,B′, C′)

Subscripts

c	coffee sample
E	coffee extract
o	initial condition (e.g., t_0 = initial soaking time, 5 min)
s	dissolved solids
(Test K)	reference extraction test of fresh coffee using pure water (tests A and A′)
(Test P)	extraction test of fresh coffee using previously enriched extract (tests C and C′)

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