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The effect of temperature, pressure, and grind size on Total Dissolved Solids (TDS) and extraction yield of semi-automatic espresso machines

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Abstract

The number of coffee shops in Indonesia has grown from 1,083 stalls in 2016 to over 2,937 booths in 2019, representing a threefold growth. Coffee shop establishments must provide two essential kinds of equipment: espresso machines, which use pressure, and filter machines, which employ infusion. The issue lies in the exorbitant cost and immense power requirements of semi-automatic and automated espresso machines, which necessitate the use of a manual espresso machine for commercial operations. The equipment can generate satisfactory espresso but encounters several challenges; specifically, the espresso generated is characterized by inconsistency, constantly varying in quality. This might arise due to the erratic nature of the manufacturing process. The two objectives of this study are: (1) to design an economically efficient semi-automatic espresso machine capable of producing products that meet the international quality standards set by the Specialty Coffee Association (SCA standard) and (2) to investigate the impact of critical factors such as pressure, temperature, and grind size, on the consistent quality of the resulting coffee (measured by Total Dissolved Solids (TDS) and extraction yield (EXT)). The research employs the Research and Development (R&D) methodology. The research findings indicate that the optimal levels of Total Dissolved Solids (TDS) and extraction yield (EXT) may be attained by using a pressure setting of 8 bars, a temperature of 90ºC, and a grind size of 3.2 on the scale. The technique for optimizing the response resulted in Total Dissolved Solids (TDS) levels of 10.03% and extraction yield (EXT) values of 19.56%. The results have been deemed acceptable based on the criteria set by the global standards of Specialty Coffee Association (SCA).

Keywords:
Espresso coffee, semi-automatic system, pressure, temperature, grind size.

1 Introduction

Coffee is highly favored globally. The coffee bean output in the year 2018/2019 amounted to 170.22 million bags, showing a 4.6% increase compared to the previous year, 2017/2018 [1]. Coffee is a universally consumed beverage that may be made using many methods. An Italian coffee-making method known as "espresso" is widely used, consuming over 50 million cups daily [2]. According to a nationwide poll conducted in the United States, 75% of Americans consume coffee, with 49% drinking more than one cup daily [3]. Coffee extraction is the process of dissolving the soluble elements of ground coffee beans in a liquid solvent [4]. Espresso extraction and brewing are the main techniques used for brewing coffee [5]. Coffee brewing involves extracting several chemical compounds from roasted coffee using solid-liquid extraction. The process parameters significantly influence the extraction kinetics of these compounds. While the extraction of coffee often lasts just a few minutes, it directly impacts the ultimate quality of the brewed coffee.

Espresso Coffee (EC) is a beverage that combines ground coffee and boiling water under specific pressure conditions. It is characterized by a layer of foam consisting of tiny bubbles arranged in a particular pattern on top of an emulsion of small oil droplets, sugar, and microscopic acids, with dispersed gas bubbles [6]. Espresso coffee is a renowned beverage noted for its distinct fragrance and intended for quick consumption [2]. This espresso coffee has distinctive sensory attributes due to its specific physical-chemical features, such as a robust body, a rich and delicate scent, a harmonious combination of bitter and sour flavors, and a long-lasting aftertaste [6]. The brew and brewing process may be characterized by two significant parameters: Total Dissolved Solids (TDS) and extraction yield (EXT) [7]. Experiments indicate that greater TDS correlates with bitterness, smokey, and roast-like scents, whereas higher TDS and low E correlate with sourness and citrus. Lower TDS correlates with enhanced sweetness and tea-like or floral fragrances at low or high E [8]. Total Dissolved Solids (TDS) is an instrument used to assess the quality of espresso. This instrument has been worldwide standardized by the Specialty Coffee Association (SCA), as seen in Fig. 1 [9]. Based on the espresso brewing control chart, the quality of espresso produced can be determined whether it is weak, strong, under-extracted, over-extracted or of good quality. Good quality espresso coffee can be achieved when Total Dissolved Solids (TDS) is in the range of 8%-12% and extraction yield (EXT) is in the range of 18%-22%.

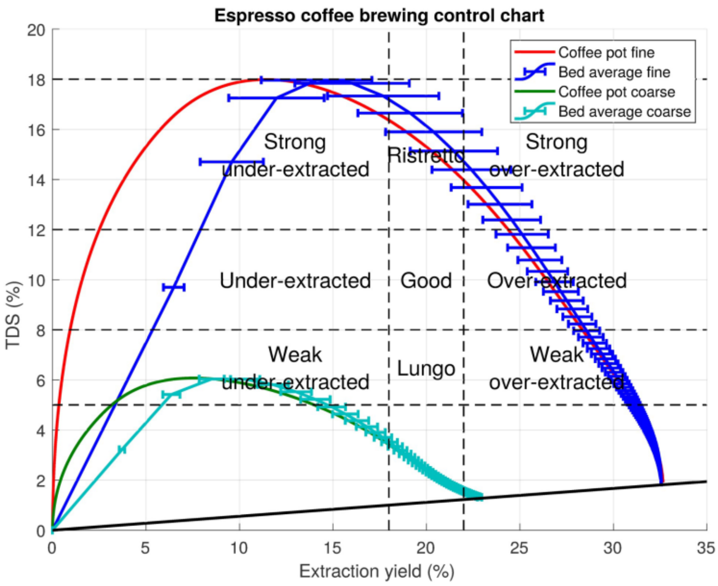


Fig. 1. Espresso brewing control chart [9].

In 2021, Indonesia's coffee production reached 12.10 million bags, each containing 60 kg of coffee beans, as the International Coffee Organization (ICO) reported. The data indicates a growth of 5.80% compared to the previous year [10]. In Indonesia, the consumption of coffee has risen by 1.7% compared to the previous year, reaching a total of 5.00 million bags [10]. In 2016, coffee was Indonesia's fifth biggest export commodity, accounting for a trade value of $1.01 billion. This amount represented 3.94% of the total value of plantation products, which amounted to $25.58 billion [11]. The Directorate General of Plantations reports that Indonesia's coffee output in 2022 amounted to 1,262,590 tons

[12]. The research indicates that the coffee business in Indonesia has significant prospects for growth. The proliferation of coffee cafes in Indonesia ensued. This phenomenon is evident from the notable surge in the number of coffee shops and the rise in household coffee consumption in recent years. The number of coffee shops in Indonesia has grown threefold, from 1,083 in 2016 to 2,937 in 2019. This upward trend in coffee shop establishments is ongoing [13].

A wide range of techniques, strategies, and instruments are used in the process of coffee preparation [14]. The growth of coffee shops in Indonesia has been subject to fluctuations as a result of various challenges faced by each business entity. A problem that arises is the tool's lack of completeness [15]. The coffee extraction techniques that are most often investigated are the espresso method (using pressure) and the filter method (using infusion) [5]. Accordingly, coffee shop proprietors must possess the capability to provide two categories of equipment: the espresso technique (utilizing pressure) and the filter method (employing infusion).

As per the SCA standard 350-2021, espresso coffee equipment is categorized into three types: manual espresso machines, semi-automatic espresso machines, and fully automatic espresso machines [16]. A manual espresso machine is a kind of espresso machine that utilizes a hand-operated lever to provide the necessary pressure for brewing the espresso. A semi-automatic espresso machine requires manual initiation and termination of the espresso preparation process. Still, it incorporates a mechanical or electromechanical device, such as a push button, to assist the user. A super-automatic espresso machine is an espresso machine that can grind entire coffee beans and store them in the brewing group. The machine then automatically adjusts the temperature and brews the coffee simultaneously.

The issue lies in the excessive pricing and substantial power requirements of semi-automatic and full-automatic espresso machines, which compel businesses to use manual espresso machines. Fig. 2 displays a selection of manual espresso machines, including the *rokpresso*, *manupresso*, and *lovepresso*. The espresso machine used in this study is a development of one of these manual espresso machines, namely the rokpresso.

Fig. 2. Manual espresso machines (a) rokpresso, (b) lovepresso, and (c) flair.

According to the feedback from some business actors, it was previously said that the equipment had the potential to make high-quality espresso. However, they encountered several challenges: the espresso produced is inconsistent, constantly varying in quality. This problem may occur because of the erratic manufacturing process, characterized by fluctuating power usage, irregular brewing temperature and duration, and variable grind size. It is imperative to create an economical semi-automatic espresso machine that operates with minimal energy consumption, is simple to maintain, and makes coffee extracts that adhere to international standards, a product currently unavailable on the market.

According to research, temperature has a considerable impact on the extraction kinetics of espresso components, including Total Dissolved Solids (TDS) [17]. Lowering the brewing temperature may lessen health risks while preserving flavor [18]. The ideal temperature for espresso varies according to the kind, with Arabica and Robusta Natural blends recommended at 92°C [19]. Studies have shown that the quality of espresso coffee is notably influenced by water pressure, since higher pressures result in greater extraction of Volatile Organic Compounds (VOCs) [20]. These results align with the observations made by Andueza [21], who found that using greater pressure (11 atm) led to a clear differentiation of espresso coffees based on their physical, chemical, and sensory attributes. Nevertheless, these studies have not explicitly discussed the impact of pressure on the extraction of Total Dissolved Solids (TDS), particularly in espresso. Additional study is required to explicitly examine the impact of pressure on Total Dissolved Solids (TDS) in espresso.

The objective of this study is to ascertain the impact of crucial variables (such as variations in temperature, pressure, and grind size) that consistently influence the quality of the outcomes (total dissolved solids and extraction yield) and find the variable that produces the most optimal Total Dissolved Solids (TDS) and extraction yield (EXT).

2 Research Methods/Materials and Methods

The research methodology used in this study is the Research and Development (R&D) approach, since it aims to develop a semi-automatic espresso machine while evaluating its effectiveness. To manufacture these products, longitudinal research and development are required; specifically, research is conducted in phases, beginning with a requirements assessment and continuing through additional study that evaluates the products' efficacy to ensure their optimal operation in the larger community [22]. Research and development is widely recognized as the driving force in the industrial sector for generating innovative items that are highly sought after by the market.

The research and development (R&D) approach encompasses 10 distinct phases, ranging from the identification of possible issues to the phase of large-scale manufacturing [22]. Fig. 3 illustrates the several steps involved in the research and development (R&D) process. Prior studies have conducted steps 1 to 6 outlined in this research. The six steps include discovering potential issues, collecting data, product design, validation, modification, and product development and testing.

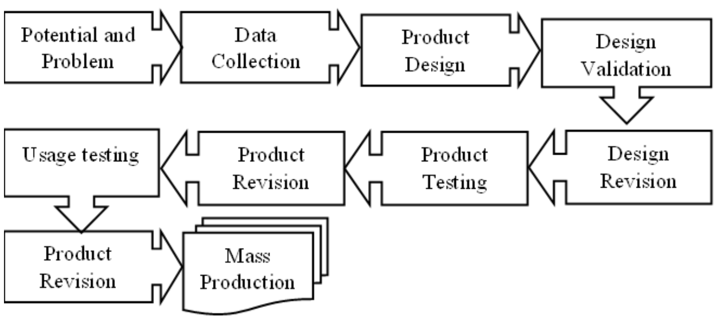
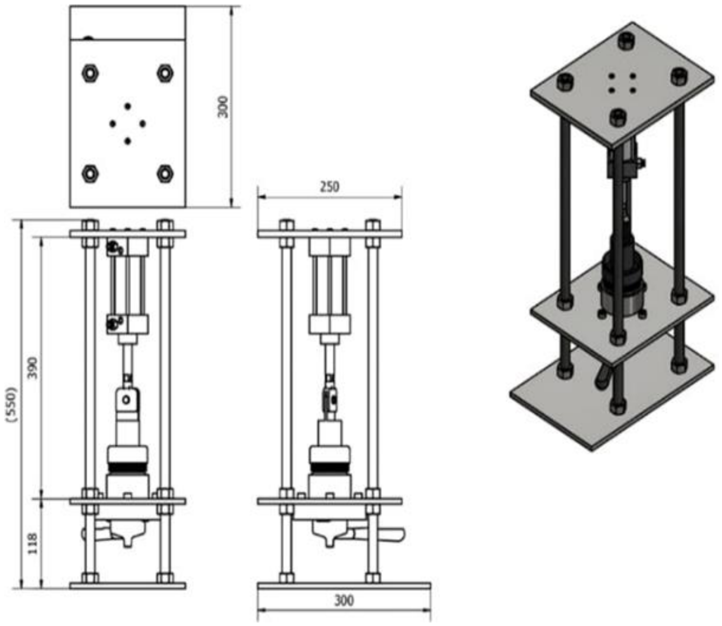
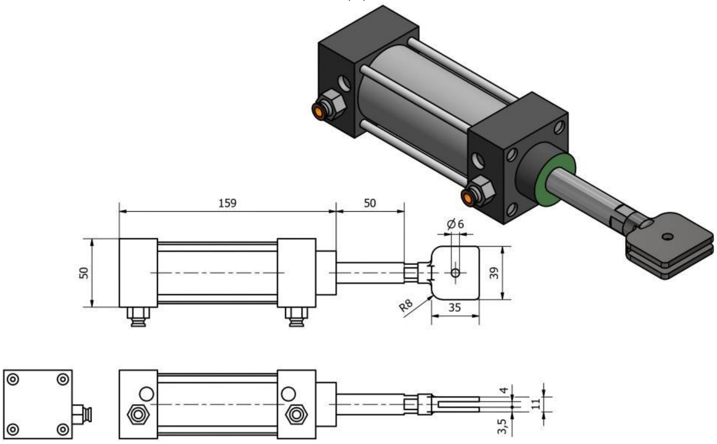


Fig. 3. Steps for using the Research and Development (R&D) method [23].

The espresso machine has been effectively designed, as seen in Fig. 4. The components of this machine are a frame, cylinder, housing plate, double-acting pneumatic actuator, plunger espresso, basket, and portafilter.



(a)



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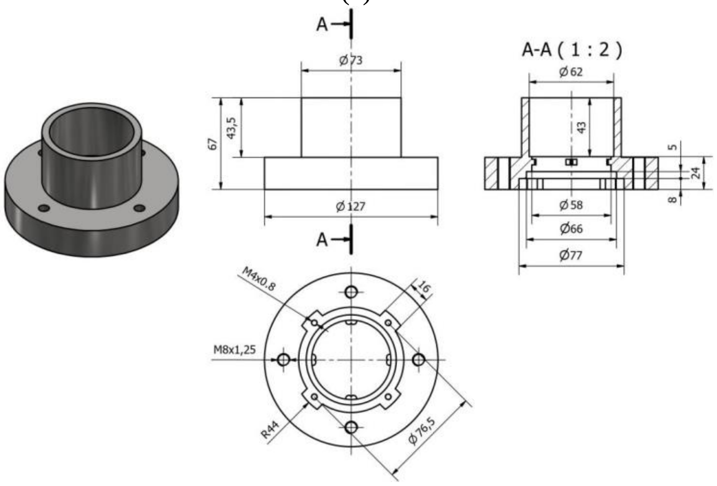


(c)

Fig. 4. (a) Design of an espresso machine, (b) design of pneumatic part, and (c) design of cylinder [23].

This circuit employs an indirect control system, as seen in Fig. 5. The pneumatic circuit comprises a double-acting cylinder, a 5/2 double solenoid, a compressor, and an air service unit. The piston in the double-acting cylinder goes forward at maximum velocity, but while retracting, the velocity is intentionally limited to just 40%. To do this, a unidirectional flow control valve is inserted into the circuit. The electro-pneumatic circuit comprises a relay, pushbutton, and solenoid valve. When an electrical current is applied to the circuit, the piston in the double-acting cylinder is positioned in a forward direction. De-pressing button 2 will cause the piston to retract. Ideally, when pushbutton 1 is pushed, the piston will advance.

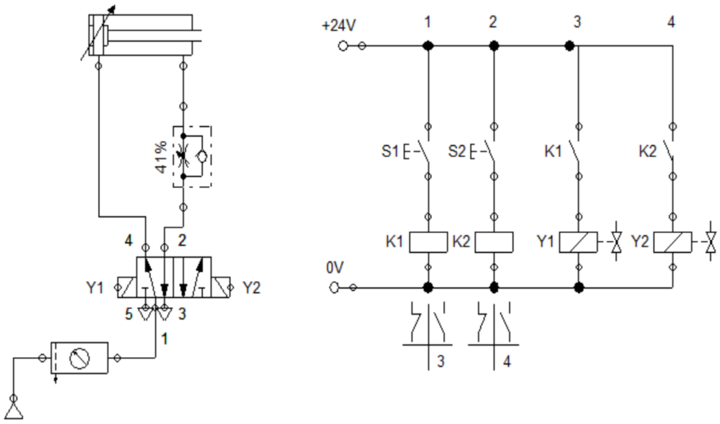


Fig. 5. Wiring diagram of the control system for the coffee machine [24].

During the preliminary phase of product testing, which centered on product functionality, it become evident that the product was operating correctly and capable of producing coffee extraction. Nevertheless, there were still some issues or hurdles that need more enhancement.

Issues identified throughout the product testing process encompassed: (1) The control system is experiencing instability and inconsistent timing. (2) Proper monitoring of work pressure is not possible. (3) The conformance of espresso outcomes with quality requirements has yet to be reviewed, necessitating additional product modifications or revisions.

The primary objective of this study is to enhance product quality to comply with international quality standards (SCA), as seen in Fig. 6's flowchart. Data and information collection is conducted by acquiring relevant information about the quality of espresso and the criteria used. This investigation used the Specialty Coffee Association (SCA) standard as the quality benchmark.

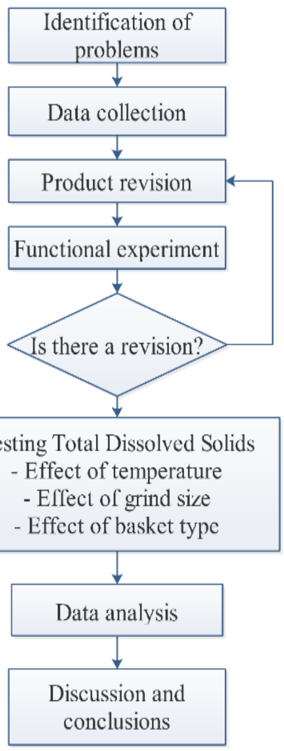


Fig. 6. Research flowchart.

Table 1 presents the identified standard parameters for espresso machine quality based on the aforementioned standards [16]. Product revision is conducted as a subsequent action to address identified issues. Areas requiring improvement include the automated control system, operating pressure regulation system, enhancement of the portafilter basket mechanism, consistency of grind size, temperature accuracy, and coffee mass adjustment. The subsequent phase involves conducting functional testing on the espresso machine. If the outcomes fail to fulfill the functional criteria of the product, more modifications are required until it is certain that the machine is operating correctly in terms of functionality.

Table 1. Standard espresso machine quality specifications [16].

Specification	Cafe grade espresso machine	Competition grade espresso machine	Test method
Number of groups	2.3 or 4	3	7.1
Automation	Semi-automatic or automatic	Semi-automatic or automatic with the capability to operate as semi-automatic	7.1
Number, characteristics, and location of steam wands	One (1) or more, non-automated and near of machine	Two (2) non-automated, one near each end of machine	7.1
Hot water spout	Present		
Brew temperature reproducibility (individual group)	Maximum temperature deviation shall be twice the standard deviation of all 14 overage brew temperatures obtained in the test series		7.3
Temperature consistency	Average brew temperature (as defined in A.5.2) of between 90.5^{0}C and 96^{0}C, with a maximum individual group brew temperature reproducibility (per A.5.3) of 1.5^{0}C	Average brew temperature (as defined in A.5.2) of between 90.5^{0}C and 96^{0}C, with a maximum individual group brew temperature reproducibility (per A.5.3) of 1.1^{0}C	7.3
Maximum intergroup temperature consistency	1.5^{0}C	1.1^{0}C	7.3
Pressure difference	Maximum Δ of 0.4 bar (6 psi) measurements. The machine shall perform reliably, without a gross change in pressure ramping (Δ ≤ 0.4 bar) when operating multiple groups to one group		7.4
Outcoming brew concentration	9%-10%		7.5
Outcoming extraction yield	18%-22%		7.5

Subsequently, it is necessary to evaluate the Total Dissolved Solids (TDS) concentration in the resulting espresso. The research examined the impact of temperature, pressure, and grind size on the independent factors. The dependent variables measured were Total Dissolved Solids (TDS) and extraction yield (EXT) levels. The study also included extraction time and yield volume as control variables. Table 2 displays the variables and their corresponding values for analyzing the test parameters.

Table 2. Factors of the variables studied and their respective levels.

Factor	Levels		
	1	2	3
Temperature (^{0}C)	90	95	100
Pressure (bar)	8	9	10
Grind size level (scale)	2.8	3.2	3.6

The Full Factorial Design of Experiments (FFD) was used to identify the factors that have a substantial impact on the quality of the espresso being made. The comprehensive factorial design of the tests conducted will provide the most crucial response data about the impacts and interactions of the primary elements [25]. The complete factorial design enables the optimization of both important and less influential factors in the process. Data processing in research involves the use of Analysis of Variance (ANOVA), which is performed using Minitab software.

The total Degree of Freedom (DF) represents the quantity of information included in the data. The study utilizes the provided information to make estimations for the values of population parameters that are not known. Adjusted Sums of Squares (Adj SS) quantify the amount of variance associated with various components of the model. Adjusted Mean Squares (Adj MS) quantify the extent to which a term or a model accounts for variance while considering the presence of all other terms in the model, irrespective of their arrangement. The F-value is the statistical measure used to assess the association between any term in the model and the response variable, which includes covariates, blocks, factor terms, and curvature. The p-value is a statistical metric that quantifies the strength of evidence against the null hypothesis. Reduced probability provides more compelling evidence against the null hypothesis.

3 Results and Discussion

The experimental design matrix in Table 3 tallied all quantitative data, such as Total Dissolved Solids (TDS) and extraction yield (EXT) levels. Subsequently, the required statistical analysis was performed. ANOVA assesses the likelihood that the observed outcomes are attributable to random chance. A variable is deemed statistically significant if its p-value exceeds the predetermined significance threshold. The consensus among researchers is that for an operational variable to be considered statistically significant in affecting the observed response and for the null hypothesis in ANOVA to be rejected, the p-value must be equal to or less than 0.05 [26][27].

Table 3. TDS and EXT data on liquid coffee sample test results

Run order	Pressure	Temperature (ºC)	Grid size (Scala)	Yield of coffee (g)	TDS 1 (%)	TDS 2 (%)	TDS 3 (%)	EXT 1 (%)	EXT 2 (%)	EXT 3 (%)
1	8	90	2.8	31.5	11.76	11.74	11.93	23.15	23.11	23.49
2	8	90	3.6	32.3	9.03	9.05	9.04	18.17	18.17	18.19
3	8	90	3.2	31	9.65	9.58	9.56	18.7	18.56	18.52
4	8	95	2.8	31.2	12.15	12.21	12.22	23.69	23.81	23.87
5	8	95	3.6	32.2	9.02	9.38	9.17	18.15	18.88	18.45
6	8	95	3.2	32.5	10.37	10.36	10.46	21.06	21.04	21.29
7	8	100	2.8	31	11.97	12.24	11.23	23.19	23.72	21.82
8	8	100	3.6	31.6	9.07	9.19	9.18	17.91	18.15	18.13
9	8	100	3.2	33	9.71	9.73	9.81	20.03	20.01	20.23
10	9	90	2.8	31	12.28	12.25	12.18	23.79	23.72	23.06
11	9	90	3.6	31.4	8.61	8.59	8.57	16.9	16.86	16.82

Run order	Pressure	Temperature (ºC)	Grid size (Scala)	Yield of coffee (g)	TDS 1 (%)	TDS 2 (%)	TDS 3 (%)	EXT 1 (%)	EXT 2 (%)	EXT 3 (%)
12	9	90	3.2	30.2	11.15	11.14	11.16	21.05	21.03	21.06
13	9	95	2.8	30.5	13.04	13.06	12.85	24.38	24.9	24.5
14	9	95	3.6	32.8	9.15	9.17	9.19	18.76	18.8	18.84
15	9	95	3.2	30.7	11.05	11.14	11.11	21.2	21.3	21.32
16	9	100	2.8	30.7	12.6	12.57	12.57	24.18	24.12	24.16
17	9	100	3.6	32.7	9.29	9.31	9.34	18.99	19.03	19.09
18	9	100	3.2	20.2	11.55	11.38	11.45	21.82	21.48	21.61
19	10	90	2.8	30.7	10.99	11.02	11.09	21.09	21.14	21.18
20	10	90	3.6	32.9	8.32	8.43	8.26	17.11	17.33	16.98
21	10	90	3.2	30.3	10.78	11.02	10.9	20.41	20.87	20.54
22	10	95	2.8	31.6	12.28	12.26	12.28	24.25	24.21	24.25
23	10	95	3.6	32.1	9.61	9.59	9.6	19.21	19.24	19.24
24	10	95	3.2	30.2	10.59	10.5	10.54	19.99	19.25	19.89
25	10	100	2.8	31.2	12.73	12.67	12.8	24.62	24.71	24.96
26	10	100	3.6	32.5	8.97	8.74	8.64	17.79	17.75	17.55
27	10	100	3.2	31.7	10.73	10.69	10.77	21.24	21.18	21.34

Table 4 demonstrates that temperature, grind size, and pressure statistically impact the levels of Total Dissolved Solids (TDS) with a confidence level of 100%. This importance is corroborated by their p-values, which are less than 0.05, on the assumption that all small effects indicate mistakes. Furthermore, the research shows that temperature, grind size, and pressure have a statistically significant influence on extraction yield (EXT) levels, with a confidence level of 100%. Table 5 presents the test results for Total Dissolved Solids (TDS) and extraction yield (EXT) for each test, considering changes in pressure, temperature, and grind size.

Table 4. Analysis of variance of total dissolved solids

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	6	144.836	24.1394	143.07	0.000
Linear	6	144.836	24.1394	143.07	0.000
Pressure	2	5.466	2.7330	16.20	0.000
Temperature	2	4.112	2.0559	12.18	0.000
Grind size	2	135.258	67.6292	400.82	0.000
Error	74	12.486	0.1687		
Lack-of-fit	20	11.647	0.5823	37.47	0.000
Pure error	54	0.839	0.0155		
Total	80	157.322			

Table 5. Analysis of variance of extraction yield

Source	DF	Adj SS	Adj MS	F-value	P-value
Model	6	430.197	71.699	130.22	0.000
Linear	6	430.197	71.699	130.22	0.000
Pressure	2	7.717	3.859	7.01	0.002
Temperature	2	23.110	11.555	20.99	0.000
Grind size	2	399.370	199.685	362.68	0.000
Error	74	40.743	0.551		
Lack-of-fit	20	37.160	1.858	28.00	0.000
Pure error	54	3.583	0.066		
Total	80	470.940			

Due to insufficient error estimates for ANOVA analysis, three repeats of the complete factorial design were deemed inadequate. Consequently, Normal Probability Plots (NPP) and Pareto plots were used to find more extensive and potentially significant effects. Variables that have a statistically significant impact may be seen on the Pareto graph when they are above the threshold [28]. Fig. 7(a) depicts a Pareto graph demonstrating all factors' substantial impact on Total Dissolved Solids (TDS) levels. This is evident from the Pareto graph, where all variables are above the threshold of 1.983. At a significance level of 5%, the Pareto diagram clearly shows that pressure, temperature, and grind size significantly impact the levels of Total Dissolved Solids (TDS). Fig. 7(b) of the Pareto chart demonstrates that all factors substantially impact the extraction yield (EXT). Pressure, temperature, and grind size substantially affect the extraction yield (EXT). This evidence is seen in the Pareto chart when the pressure, temperature, and grind size variables surpass the threshold of 1.993. At a significance level of 5%, the Pareto diagram clearly shows that pressure, temperature, and grind size significantly impact the extraction yield (EXT).

Fig. 8 displays the primary plot representing Total Dissolved Solids (TDS) and extraction yield (EXT) levels. By analyzing the primary plots, it becomes evident that pressure and temperature have little impact on the Total Dissolved Solids (TDS) and extraction yield (EXT) in comparison to other factors, namely grind size. The grind's size substantially impacts the overall amount of dissolved solids (TDS) and the extraction yield (EXT) obtained. Increasing the grind size value will generally decrease the Total Dissolved Solids (TDS) and extraction yield (EXT) generated. This finding is consistent with the outcomes of other investigations [29].

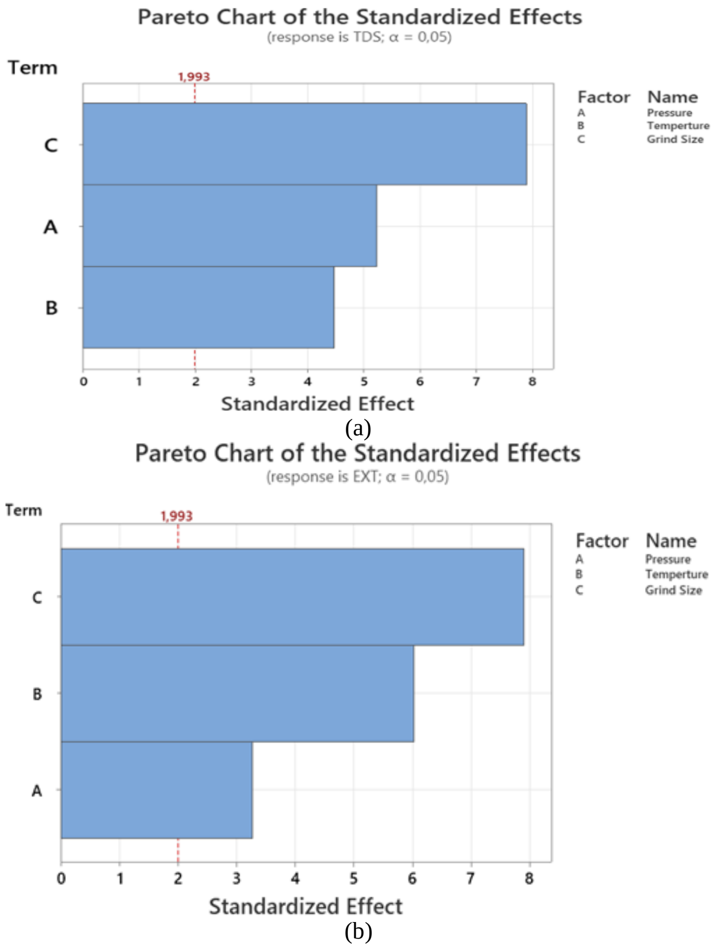
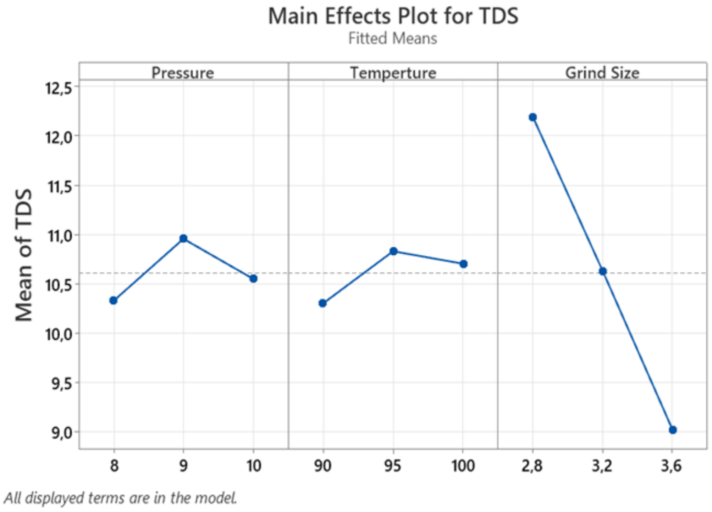
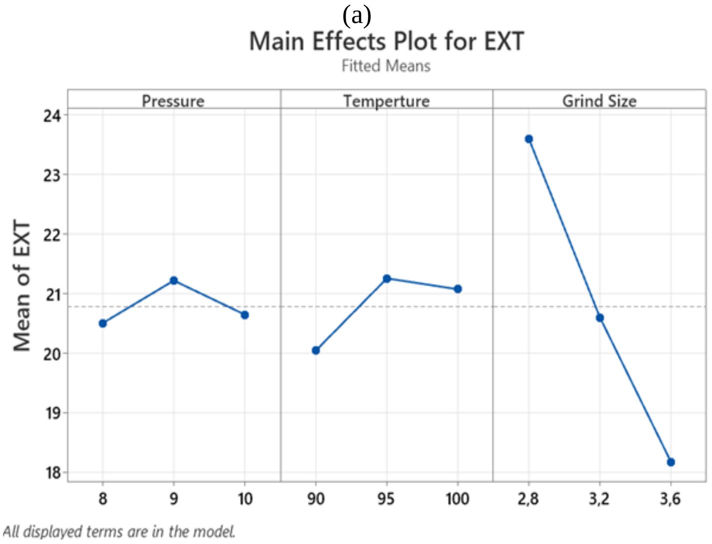


Fig. 7. Pareto charts for (a) Total Dissolved Solids (TDS) and (b) extraction yield (EXT).



(a)



(b)

Fig. 8. Main plots graphs for (a) total dissolved solids (TDS) and (b) extraction yield (EXT).

The quality of brewed coffee is primarily determined by two crucial factors: the Total Dissolved Solids (TDS), which refers to the proportion of soluble solids in the brew by weight, and the Extraction Yield (EY), which represents the proportion of soluble solids extracted from the coffee grounds. These parameters reflect the strong, weak, bitter, or sour taste of the coffee. The recommended Total Dissolved Solids (TDS) range for brewed coffee in SCA barista's practice is 1.15%–1.35%, with an extraction yield (EY) of 18%–22%. For espresso coffee, the TDS should be between 8%-12%, with an extraction yield (EXT) of 18%-22% [30]. A higher extraction yield (EXT) level indicates that the resulting espresso will have a more bitter taste, whereas a lower extraction yield (EXT) level would result in a more pronounced sour taste. Similarly, a larger concentration of Total Dissolved Solids (TDS) will result in a stronger espresso, whereas a lower concentration of TDS will provide a weaker espresso.

The response optimizer approach allows for precise control of factors or components to get the highest quality of espresso by manipulating ideal circumstances. The objective of this response optimization technique is to get the most favorable outcomes, namely the ideal levels of Total Dissolved Solids (TDS) and extraction yield (EXT). Fig. 9 depicts the optimization plot showcasing the intended answer. Composite desirability (D) is an additional statistical metric that may be used to evaluate the precision of response optimization [26][31]. The D value approaching 1.00 indicates a high level of reliability and precision in the optimization outcomes, as determined by the statistical analysis of variables and response optimization [32]. The composite desirability is 0.9234, which is the result of optimizing the response for the levels of Total Dissolved Solids (TDS) and extraction yield (EXT). Based on this value, it may be inferred that the optimum conditions identified from the optimization plot are highly dependable and consistent with the rigorously verified regression model. Fig. 5 demonstrates that the factors that generate the most appropriate levels of Total Dissolved Solids (TDS) and extraction yield (EXT) are a pressure 8 bars, a temperature of 90^{0}C, and a grind size of 3.2. The response optimization approach yields Total Dissolved Solids (TDS) at a level of 10.03% and extraction yield (EXT) at a level of 19.56%. The outcomes of this response optimization approach yielded improved results compared to earlier research in terms of Total Dissolved Solids (TDS) levels and extraction yield (EXT). Specifically, the TDS levels and EXT results were 11.5252% and 22.348%, respectively.

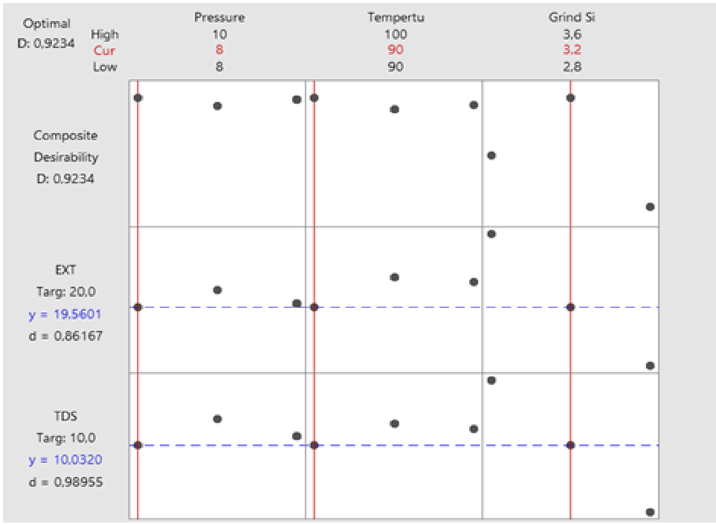


Fig. 9. The optimization plot of Total Dissolved Solids (TDS) and (b) extraction yield (EXT).

4 Conclusion

The variables of pressure, temperature, and grind size have a statistically significant impact on the levels of Total Dissolved Solids (TDS) with a confidence level of 100%. Pressure, temperature, and grind size have a statistically significant and confidently determined impact on the extraction yield (EXT). The variables that generate the ideal levels of Total Dissolved Solids (TDS) and extraction yield (EXT) are achieved by using a pressure setting of 8 bars, a temperature of 90ºC, and a grind size of 3.2 on the scale. The response optimization strategy yielded Total Dissolved Solids (TDS) levels of 10.03% and extraction yield (EXT) values of 19.56%. These findings are acceptable according to the criteria established by the worldwide standards of Specialty Coffee Association (SCA).

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