A NOVEL OPTIMIZED ENERGY-SAVING EXTRACTION PROCESS ON COFFEE

by

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In this paper, Taguchi method is applied to optimize ultrasound thermal process for extracting caffeine and flavor from coffee. The use of ultrasound can abridge experiments in cost, energy loss and time; the different operating conditions for extraction experiments are executed and the results are also compared. The results show that the best design factors for caffeine are 95 ℃ of extraction temperature, 28 kHz of operating frequency and 30 s of extraction time. The proposed optimized extraction method is efficient and energy-saving compared with the general process for making coffee.

Key words: *energy-saving, Taguchi, ultrasound, coffee*

Introduction

Traditional experimental design focused on the design of the factors; as long as the control factor increases, however, it often leads to the increment of the numbers of the experiments as well as the complexity of the process, however, lots of experimental factors can be simplified or removed by The Taguchi method, which is applied to decrease the numbers of experiments by using orthogonal table: firstly, select the experimental variables, secondly, determine the level of each variable, and finally, solve the analysis of variance [1]. It focuses on how to decrease the variability of experimental results, so as to find out the best combination of parameters in accordance with the beneficial results of cost [2, 3].

Ultrasonic extraction is the way of using the powerful energy which is produced by the burst of the bubbles-produced by the change of the pressure when ultrasound is in the liquid-to accelerate the contact speed of the solvent and the extract. The main feature of the approach is that it can rapidly and evenly blend the extract and the solvent; in the process of extracting useful constituents from the natural substances, it can bring the extract from the matrix to the solvent without damaging the structure of the extract [4, 5].

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The ingredients of coffee include caffeine, aroma, proteins, tannic acid, fat, etc.. When used in moderation, caffeine can stimulate the brain, enhance memory, inspire enthusiasm, clarify thought, and reduce fatigue and sleepiness. However, excessive amounts of caffeine would result in anxiety, uneasiness, heart palpitations, headaches, diarrhea, insomnia and many more. One will find the accounts on the fact that caffeine can have detrimental effects on human health in literature; these negative effects include exacerbating coronary artery disease, raising high blood pressure, and heightening the higher risk of heart attack and kidney disease [6, 7].

This paper applies Taguchi method to consider the new extraction equipment that is designed to optimize the consistency of the coffee powder and extraction liquid to allow for a highly efficient extraction process.

Experimental method

This experiment uses an ultrasonic equipment to extract caffeine and coffee flavor from coffee. By controlling the temperature, wave frequency, and time duration of each extraction, these variable effects on the caffeine concentration of each extraction can be measured as well as a comparative analysis of the extraction liquid by high performance liquid chromatography (HPLC) and gas chromatography (GC).

Description of experiment

The materials used in the experiment are RO water and Italian coffee powder. The equipment needed includes a grinding machine, a water bath, a refrigerated circulation bath, and an ultrasonic device that functions at 28 kHz and 42 kHz with GC and HPLC. To ensure a consistent and accurate temperature for each experiment, the circulation bath is utilized to either raise or lower the temperature of the coffee/RO solution. When the correct temperature for the specific experiment is reached, the coffee powder will be mixed into the RO water. This mixture is then processed through one of the two separate ultrasonic machines. One ran at 28 kHz for the duration of 15 seconds and the other ran at 40 kHz for the same amount of time. The results of these extractions are collected in collection tank 1 and collection tank 2, respectively. The process is next repeated for the duration of 30 seconds. The extraction results are also gathered into the tanks. Each collection tank then holds the solution of the two extractions.

Process of experiment

First, a grinder is employed to grind the coffee beans into fine grains and then filter them through a 40 mesh filter. When the temperature reaches the operating temperature, the mixture of coffee powder and RO water is placed into the ultrasonic equipment, and processed under various extraction conditions. The extraction liquid is initially filtered through a 40 mesh filter and collected. To achieve a ratio of extraction liquid to water of 1:9 for a final dilution of 10 times, further the extraction liquid is filtered through a 0.45 μm filter paper. And then, the coffee flavor concentration is used as the base for the comparative analysis of HPLC. The caffeine concentration, on the other hand, is used as the base for the comparative analysis of GC.

The integrity of the process and analysis is verified by using the known coffee flavor concentration of the standardized coffee. The results of the caffeine concentration of the standardized coffee are compareed with the analyzed caffeine concentration of the sample provided by the issuing laboratory. If these results are not similar, the experiment will be repeated with adjustment to the operating conditions.

Finally, these results are tabulated and the comparesons indicate the optimum values for time/frequency and temperature would produce the greatest concentrations of caffeine. The experimental process is shown in fig. 1.

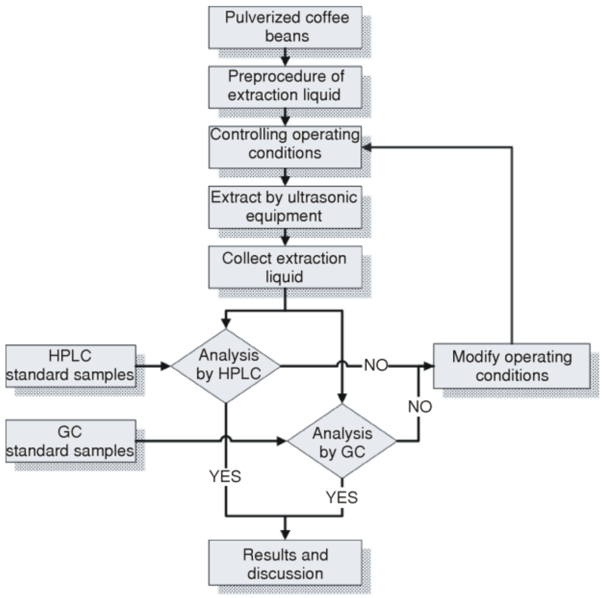

Figure 1. Process of experiment

Experimental design by Taguchi method

The orthogonal arrays of L4(2^3) are used with three factors for two levels. These three operating parameters in this experiment include: solution temperature, operating frequency and oscillation periods. The solution temperature is either 85 °C or 95 °C. The operating frequency is either 28 kHz or 40 kHz. The oscillation periods are either 15 or 30 seconds. Each experiment uses 300 ml of RO water and 30 grams of coffee powder. Each extraction is then tested for caffeine concentration. The experiment without applying Taguchi Method has to be done 40 times, which means there will be 160 times of performances of the experiment if we do 4 rounds of repetition; the experiment with Taguchi Method design, however, only needs half of the performances. Taguchi method is not only more efficient but also more convenient for the experimental planning, as shown in tab. 1.

Table 1. Experimental data of extraction

Exp.	A (temperature)	B (frequency)	C (time)
1	85 °C	28 kHz	15 s
2	85 °C	40 kHz	30 s
3	95 °C	28 kHz	30 s
4	95 °C	40 kHz	15 s

Equations of Taguchi method

The experimental results are analyzed by specific equations, including average value, standard deviation, signal to noise (SN) ratio, total variations and errors, respectively.

$$\text{Average value: } \bar{y} = 1/n \sum_{i=1}^{n} yi, \text{ Standard deviation: } S = [1/n - 1 \sum_{i-1}^{n} (y_i - \bar{y})^2]^{1/2} \quad (1)$$

$$\text{SN ratio (the smaller, the better } \frac{S}{N} = -10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{2}$$

$$\text{Total variations: } DOF_T = n\times r - 1,\ SS_T = \left(\sum_{i=1}^{n}\sum_{j=1}^{r} y_{ij}^2\right) - n\times r\times \bar{y}^2 \tag{3}$$

$$\text{Factor effects:, } DOF_A = L - 1,\ SS_A = \frac{n\times r}{L_A}\sum_{k=1}^{L_A}(\bar{y}_k - \bar{y})^2 \tag{4}$$

$$\text{Errors: } DOF_e = n\times(r-1), SS_e = \sum_{i=1}^{n} S_i^2(r-1) \tag{5}$$

Results and discussion

The optimized combination parameter of caffeine by Taguchi method

We do the 4 experiments in tab. 2 respectively and repeatedly for 3 times and thus gain the data of caffeine P1, P2 and P3; next, eq. (1) is used to calculate the average value of each experiment; then, eq. (2) is applied to obtain each error of standard. According to different demands, we determine the characteristics of the S/N ratio the smaller the values, the better. Therefore, the S/N ratio data are obtained, –43.26, –43.39, –43.96 and –42.32, by substituting the eq. (3) with the average value and standard value. The results are shown in tab. 2.

Table 2. Table of experiment records of extraction temperature at 85 °C and 95 °C

Exp.	P1 [ppm]	P2 [ppm]	P3 [ppm]	y [ppm]	S	S/N
1	150.10	144.28	141.97	145.45	4.19	–43.26
2	149.35	149.90	144.06	147.77	3.22	–43.39
3	153.36	156.05	163.91	157.77	5.48	–43.96
4	148.61	146.51	144.65	146.59	1.98	–42.32

Table 3. Table of factor effects of extraction temperature at 85 °C and 95 °C

	A	B	C
Level 1	146.61	151.61	146.02
Level 2	152.18	147.18	152.77
Effect	5.57	-4.43	6.75

Table 3 is the response table. The values of A1, B1 and C1 are the average numbers from the level 1 value they are 146.61, 151.61 and 146.02, respectively. The values of A2, B2 and C2 are the average numbers from the level 2 value they are 152.18, 147.18 and 152.77, respectively. A factor is 5.57; B factor is –4.43; C factor is 6.75; the optimized factor design is A2B1C2 parameter combination (extraction temperature is 95 °C, operating frequency is 28 kHz and extraction time is 30 s).

Table 4 is about the use of the eq. (7) to solve factor effects of A, B and C. Equation (5) is used to get the total square number of the variations 412.39. Equation (6) solves the DOF of the three factors. Equation (4) is used to get the DOF of total variations 11.

Contribution is proportional of the square of each factor, like (93.07/412.39)·100% = 22.57%. Because the contribution of experiment errors of C factor is 30%, the influence of C factor is larger for the experiment.

Table 4. Table of the analysis of extraction variance at the temperature of 85 °C and 95 °C

Factor	SS	DOF	Contribution
A (temperature)	93.07	1	22.5697%
B (frequency)	58.87	1	14.2766%
C (time)	136.69	1	33.1454%
Error	123.75	8	30.0083%
Total	412.39	11	100%

The optimized parameter of coffee flavor by Taguchi method

Tab. 5 displays the optimized parameters of coffee flavors, including 2-Methoxy-3-Methylpyrazine, 2-Pheynlethanol, Capric Acid, and 4-Tridecanone by the known factor effects. For 2-Methoxy-3-Methylpyrazine, 2-Pheynlethanol and Capric Acid, they have the optimized parameters when the temperature is 85 °C, the operating frequency is 28 kHz and the extraction time is 15 s. For 4-Tridecanone, nevertheless, it has the best parameters when the temperature is 95 °C, the operating frequency is 40 kHz and the extraction time is 15 s.

Table 5. Table of the best parameters of coffee flavors

Coffee flavor	Temperature	Operating frequency (28 kHz)	Operating frequency (40 kHz)	Extraction time (15 s)	Extraction time (30 s)
2-Methoxy-3-Methylpyrazine	85 °C	■		■	
	95 °C				
2-Pheynlethanol	85 °C	■		■	
	95 °C				
Capric acid	85 °C	■		■	
	95 °C				
4-Tridecanone	85 °C				
	95 °C		■	■	

Work of extraction

Time of Extracting is maintained for 120 seconds; then, we compare the general coffee machine with ultrasound thermal method to extract the caffeine and flavor with different operating temperatures. The frequency is maintained at 28 kHz when ultrasound thermal method is used. The current consumed by the general coffee machine at 65 °C is over the interval of 5.51 to 5.55, and by the ultrasound thermal method, which is shown in tab. 6. The powers of extraction by these methods are derived from eq. 10 and the results are shown in fig. 5.

$$\text{Power} = I \times V \times \sqrt{2} \tag{6}$$

where I is current and V is voltage

From fig. 2, the power of applying ultrasound thermal process is more than using general coffee machine for extraction of coffee in 30 seconds, but decreases right after the time. Also, it can be found that the differences of powers at 35 °C and 65 °C by ultrasound thermal method are tinny, so we may raise the operating temperature higher to increase the quantity of caffeine without too much power. Accordingly, the work of extraction can then be obtained by calculating the areas under the different lines in fig. 2. The consumed work is shown in tab. 6 and be able to learn that consumed work obtained by ultrasound thermal method is always more efficient and energy-saving than using the general coffee machine. Especially, the work of the general coffee machine is 1.84 and 1.81 times the strength of ultrasound thermal process at 35 °C and 65, respectively.

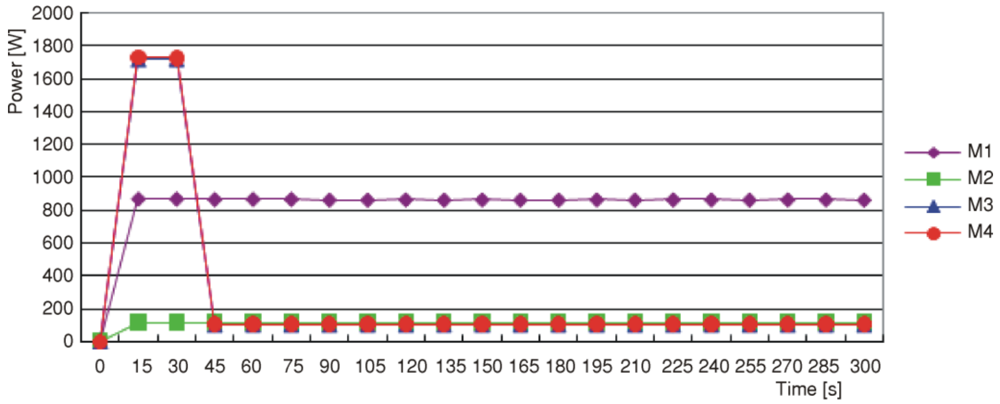

Figure 2. Power of different extraction methods (M1: general coffee machine, M2: ultrasound extraction at 5 °C, M3: ultrasound extraction at 35 °C, M4: ultrasound extraction at 65 °C)

Table 6. Work of extraction

Method / Work	General coffee machine	Ultrasound thermal method (35℃)	Ultrasound thermal method (65 °C)
Extracting 60 s	51,709	54,426	54,882
Extracting 120 s	103,045	55,974	56,641

Conclusions

From the results of these experiments, it can be concluded that the influence of oscillation periods and temperature are the most and the second important factors in determining caffeine content of an extraction by Taguchi method. From the table of S/N ratio and factor effects, at 85 °C of extraction temperature, 28 kHz of operating frequency and 15 seconds of extraction time by using Taguchi Method produces the best result in the experiment of 2-Methoxy-3-Methylpyrazine, 2-Pheynlethanol and Capric Acid. If the extraction time factor accounts for the most of total quality loss, that means the extraction time factor has the greatest influence on this kind of situation.

The consumed work of the general coffee machine is 1.84 and 1.81 times the strength of ultrasound thermal process at 35 °C and 65 °C, respectively. So, the proposed extraction method is a kind of optimized energy-saving process and can be applied to large-scale manufacture.

The results indicate the influence of temperature, extraction duration, and ultrasound frequency as well. It provides the insight into creating a more efficient, in terms of time and energy consumption, manufacturing process for caffeine and flavor concentration extraction from coffee.

Acknowledgments

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Nomenclature

I – current, [A]
V – voltage, [V]
$\overline{y}$ – average of y_i, [ppm]
y_i – caffeine or flavor signal, [ppm]

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