



Design and Optimization of an Automated Ceramic Drying System Using Arduino for Small and Medium Enterprises

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Abstract. The ceramic drying process in Small and Medium Enterprises (SMEs) often relies on ambient conditions, leading to prolonged drying times and inconsistencies in product quality. This study presents the design and optimization of an automated ceramic drying system that utilizes an Arduino-based microcontroller to regulate temperature and airflow in real-time. A full factorial experimental design was employed to investigate the influence of two critical parameters—temperature (35°C, 40°C, 45°C) and air velocity (3 m/s, 4 m/s, 5 m/s)—on drying performance. Experimental results identified the optimal condition at 45°C and 3 m/s, yielding the shortest drying time of 18.031 seconds. Statistical analysis using ANOVA confirmed the significance of temperature ($F = 34.69$, $p = 0.002$) and air velocity ($F = 6.97$, $p = 0.044$), with temperature accounting for 78.87% of the total variation. Furthermore, Signal-to-Noise Ratio (SNR) analysis based on the Smaller-the-Better criterion validated the robustness of the optimal settings. The proposed system offers SMEs a low-cost, scalable, and reliable solution, enabling improved drying efficiency, enhanced product quality, and reduced process variability through accessible automation technologies.

Keywords: ceramic drying optimization, design of experiment, full factorial design, smes productivity

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1. Introduction

Product design is a multidisciplinary process that integrates creativity, functionality, and usability to generate effective solutions tailored to user needs. Over time, design methodologies have evolved to incorporate systematic and data-driven frameworks, enabling researchers to evaluate design alternatives more rigorously. One of the most robust tools in this regard is the Design of Experiments (DoE), which provides a structured approach to investigate the influence of multiple factors on product performance through controlled and reproducible experiments [1], [2].

DoE has been extensively applied in various engineering and product development fields due to its ability to uncover both main and interaction effects among variables. Its integration with frameworks such as Kansei Engineering which links product attributes to users' emotional responses further exemplifies its versatility in optimizing functional and affective product qualities [2], [3]. In addition, participatory design approaches have gained traction in recent years, emphasizing the role of user involvement in co-creating solutions that are both contextually relevant and socially accepted [4], [5].

Effective product and process design is crucial in improving manufacturing productivity, quality, and competitiveness, especially within small and medium enterprises (SMEs). SMEs contribute significantly to economic development, accounting for over 60% of Indonesia's GDP and employing most of the national workforce [6]. However, these enterprises often face technological limitations, particularly in production processes relying on manual methods.

A compelling example of this challenge is in the ceramic manufacturing sector, where drying is critical before the bisque firing process. Traditional drying methods, which depend on ambient weather conditions, are inherently slow often requiring 3 to 5 days and highly inconsistent, increasing the risk of product defects such as cracking and warping [5]. These issues severely affect production efficiency and limit the scalability of ceramic-based SMEs.

Recent advancements in accessible automation technologies offer promising opportunities to address these bottlenecks. In particular, Arduino-based systems have demonstrated success in controlling environmental parameters for drying applications in agriculture, such as moringa leaves [7], coffee beans [8], and shallots [9]. These systems are favored for their low cost, modularity, and open-source architecture, making them ideal for SME adoption. However, ceramic materials possess distinct thermal and mechanical characteristics compared to agricultural products, necessitating a tailored optimization strategy for drying parameters to prevent surface cracking and structural stress.

Furthermore, although several studies have used DoE full factorial designs to optimise drying conditions in non-ceramic contexts [10], [11] related to food [12], chemical and pharmaceutical products [13], systematic attention to the optimisation of drying parameters for ceramic materials in Arduino-controlled systems remains limited. Furthermore, few studies have considered integrating physical space design, real-time sensor control, and statistical optimisation into a single solution tailored to the needs of SMEs.

In light of these gaps, the present study aims to design and optimize an Arduino-based automatic ceramic drying chamber by systematically analyzing the effects of temperature and airflow speed on drying time using a full factorial experimental design. The prototype is developed with cost-effective components and tested under controlled conditions to identify the most efficient drying configuration. The findings are expected to offer a practical and replicable technological solution to improve ceramic SMEs' productivity, process stability, and product quality.

2. Methods

2.1. Experimental Design and Parameter Justification

This study employed a full factorial design to investigate the effects of two process parameters, temperature and air velocity, on ceramic products' drying time. A factorial design was selected for its ability to evaluate both main effects and interaction effects, offering comprehensive insights that are difficult to achieve through one-factor-at-a-time approaches [1].

In this study, the temperature levels were set at 35°C, 40°C, and 45°C, while the airflow velocities were adjusted to 3 m/s, 4 m/s, and 5 m/s, as summarized in Table 1. These parameter ranges were selected based on both empirical and practical considerations. From an empirical standpoint, previous studies on the drying of heat-sensitive materials such as rice, tapioca, and clay-based ceramics have demonstrated that temperatures between 35°C and 45°C are optimal for accelerating moisture removal while preventing surface cracking and structural deformation [14], [15]. From a technical perspective, the chosen range also aligns with the operational stability of the experimental setup: the Arduino-controlled PTC heater and blower system functioned most efficiently within this temperature range,

avoiding risks of overheating or exceeding the material limits of the ceramic tableware.

Similarly, the selection of airflow velocities between 3 m/s and 5 m/s was informed by principles of convective drying, where this range effectively balances the drying rate and uniformity [12]. Excessively high airflow can lead to surface hardening and internal moisture retention, while airflow that is too low may cause stagnation and prolong the drying process. Each combination of temperature and airflow (a total of 9 treatments) was replicated twice, resulting in 18 experimental runs. To reduce environmental and procedural bias, the order of experiments was randomized using a random permutation generator.

Table 1. Control factors and levels

Control factors	Code	Level		
		1	2	3
Temperature	A	35	40	45
Air Velocity	B	3 m/s	4 m/s	5 m/s

2.2. Prototype Development

The drying system was constructed as a prototype using an acrylic chamber with dimensions of $40 \times 30 \times 30$ cm, as shown in Figure 1. The setup incorporated several key components that worked together to maintain the desired drying conditions. An Arduino Uno microcontroller served as the central control unit, coordinating sensor readings and actuator responses. A DHT11 sensor was used to continuously monitor the temperature and humidity inside the chamber, while a PTC heater functioned as the primary heating element. Airflow within the chamber was generated and regulated by a DC blower, and a relay module enabled automated switching of the heater based on the control signals from the Arduino. The entire system was powered by a 12V adapter serving as the main power supply for the circuit.

During operation, temperature readings were constantly monitored, and the relay controlling the PTC heater was activated or deactivated according to a predefined set temperature using a simple hysteresis-based control logic, as illustrated in Figure 2. The airflow velocity was manually adjusted by varying the blower output, and its value was measured using an anemometer positioned at the center of the chamber to ensure accurate readings.

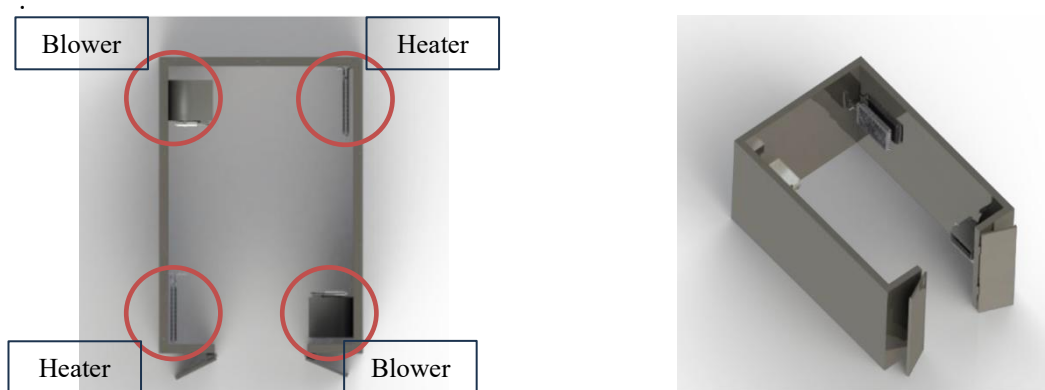


Figure 1. prototype drying chamber

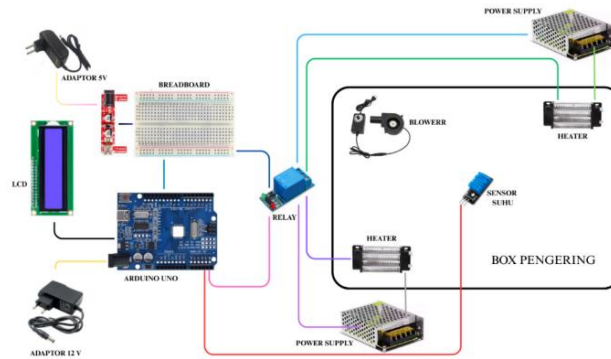


Figure 2. Prototype Schematic

2.3. Data Collection and Inspection

Each ceramic sample was dried under the predefined conditions until a stable mass was reached ($\pm 0.01\text{g}$ over 5 minutes). Drying time was recorded in seconds, from the initial heater activation to the final stable weight measurement. After drying, all samples were visually inspected under illumination for surface defects such as cracks or warping.

2.4. Statistical Analysis

To ensure the validity of parametric tests, data were first tested for: Normality, using the Shapiro-Wilk test, with $p > 0.05$ indicating a normal distribution. Homogeneity of variances was measured using Levene's test, with $p > 0.05$ confirming equal variance across groups. Subsequently, a two-way ANOVA was performed to assess the main and interaction effects of temperature and air velocity on drying time. An F-statistic with $p < 0.05$ was considered statistically significant. The percentage contribution of each factor was calculated based on the sum of squares. Additionally, a Signal-to-Noise Ratio (SNR) analysis was conducted based on the Smaller-the-Better criterion (Taguchi method), which is suitable for objectives that aim to minimize the response variable—in this case, drying time. The SNR value was used to assess the stability and robustness of the drying performance across treatment levels. Figure 3 illustrates the research framework adopted in this study.

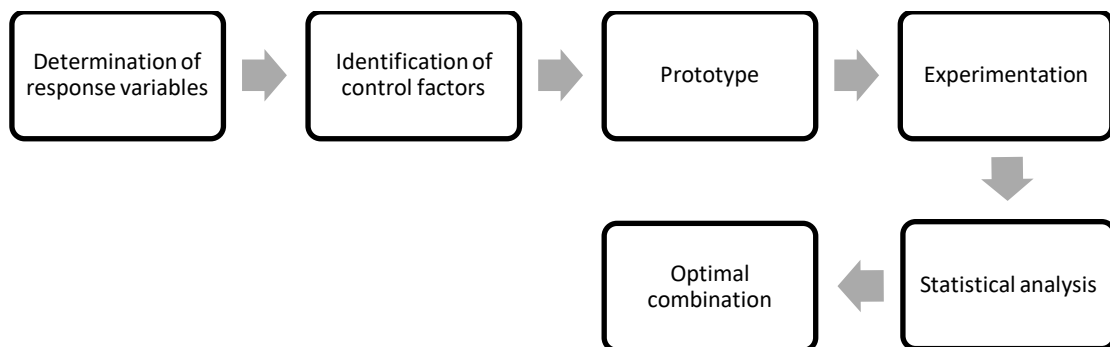


Figure 3. Research flow

3. Results and Discussion

3.1. Experimental Results and Descriptive Statistics

The full factorial experiment produced drying time data for nine temperature and air velocity combinations, each replicated twice (Table 2). The shortest average dry chamber's geometry d_s was achieved at a temperature of 45°C and an airflow velocity of 3 m/s , while the longest drying time exceeded 50 seconds under the lowest settings (35°C , 3 m/s).

Table 2. Experiment Results

Trial	Control factors		1 st	2 nd	Mean	SNR
	A	B	Replication	Replication		
			Drying time (s)	Drying time (s)		
1	1	1	50,440	39,633	45,036.5	-93,133
2	1	2	46,830	32,407	39,618.5	-92,099
3	1	3	28,859	32,417	30,638	-89,740
4	2	1	43,228	36,027	39,627.5	-91,996
5	2	2	28,800	25,253	27,026.5	-88,655
6	2	3	21,607	25,215	23,411	-87,414
7	3	1	18,030	18,032	18,031	-85,120
8	3	2	21,625	21,623	21,624	-86,699
9	3	3	21,610	18,000	19,805	-85,971

A statistical analysis was conducted to strengthen the experimental findings. The normality test using the Shapiro–Wilk method indicated that the data were normally distributed ($p > 0.05$), thereby allowing further parametric analysis [16], [17]. Subsequently, the homogeneity of variances was evaluated using Levene’s test, which showed that the group variances were homogeneous ($p > 0.05$), thus satisfying the assumptions for ANOVA [18]. The ANOVA was performed to assess the effects of two primary factors temperature and air velocity on the drying time of ceramic products. The results revealed that temperature significantly affected drying time ($F = 34.69$; $p = 0.002$), while air velocity also exhibited a statistically significant influence, albeit to a lesser extent ($F = 6.97$; $p = 0.044$). In contrast, the interaction between temperature and air velocity was insignificant ($F = 0.19$; $p = 0.834$), indicating that each factor independently influences the drying process. These findings confirm that temperature is the most influential factor in the ceramic drying process surpassing the effect of air velocity and are consistent with thermal-drying principles showing that the temperature gradient between the material surface and ambient air strongly governs the evaporation rate [19], [20].

3.2. Effect Size and Confidence Intervals

The statistical analysis confirmed that the data met the assumptions of normality and homogeneity, validating the use of ANOVA. The ANOVA results indicated that both temperature and air velocity had significant effects on drying time, with temperature emerging as the dominant factor, while their interaction was not statistically significant. These findings underscore that temperature plays a primary role in accelerating the ceramic drying process, in line with thermal-drying theory whereby the temperature gradient between the material surface and the surrounding air governs the evaporation rate [19], [20].

As a complement to significance testing, partial eta-squared (η^2) was computed to quantify effect sizes following the two-way ANOVA. Temperature exhibited a large effect ($\eta^2 = 0.789$), indicating that ~79% of the variance in drying performance is attributable to temperature settings; air velocity showed a moderate effect ($\eta^2 = 0.158$), and the interaction was negligible ($\eta^2 = 0.009$). These interpretations align with conventional benchmarks for η^2/η^2_p ($\approx .01$ small, $\approx .06$ medium, $\approx .14$ large) and reporting guidance for ANOVA effect sizes [21]. To assess estimate precision, 95% confidence intervals (CIs) were calculated for each temperature: at 35 °C, 95% CI = [40.82, 46.26]; at 40 °C, 95% CI = [24.73, 30.32] s; and at 45 °C, 95% CI = [18.00, 20.11] s. The narrow CI at 45 °C indicates low variability and thus high stability and repeatability at this setting, consistent with CI theory that narrower intervals reflect more precise estimates [22]. Collectively, these indicators show that temperature is not only statistically significant but also practically consequential and reliable as a design parameter in ceramic drying.

3.3. Signal-to-Noise Ratio (SNR) Analysis

To evaluate the robustness and consistency of each parameter setting, the Taguchi method was applied using the Smaller-the-Better Signal-to-Noise Ratio (SNR) criterion, which is appropriate for response variables intended to be minimized, such as drying time [23]. The SNR analysis revealed that the highest performance was achieved at temperature level 3 (45 °C) with an SNR value of –85.120 dB, and airflow level 1 (3 m/s) with an SNR value of –86.69 dB. These levels correspond to the shortest average drying time and the lowest variability, indicating a highly robust process in the Taguchi sense i.e., maximizing SNR (even if numerically negative in dB) reflects reduced sensitivity to noise factors [23].

The combination of 45 °C and 3 m/s represents the optimum setting because it minimizes the average drying time and yields the most robust performance across replications, as confirmed by the highest SNR values (-85,120). This outcome reinforces the reliability of the selected parameters and supports their practical application in ceramic drying systems, consistent with prior Taguchi-based optimizations in ceramic/tableware processes where SNR-guided settings reduced defects and stabilized performance [24]

3.4. Comparison with Existing Drying Technologies

Compared to conventional drying at ambient temperature, which typically requires 3–5 days, and an Arduino-controlled oven system with a drying time of approximately 18,031 seconds (300.5 minutes), the proposed system demonstrates a notable improvement in drying efficiency. In addition, product quality is maintained, as no cracks or deformation were observed. These results indicate that an oven system with controlled airflow and temperature can effectively reduce drying time. Furthermore, energy consumption is relatively lower due to the compact drying chamber and more targeted heat distribution. Unlike large-scale industrial drying systems, the developed system utilizes a 12V PTC heater and a blower with controlled operation, making it more suitable for small-scale production.



Figure 4. Ceramic products quality inspection results

Studies using similar Arduino-controlled systems in agricultural contexts [7], [8], [9] reported efficiency improvements; however, no prior work focused specifically on ceramic materials, which have more rigid thermal handling requirements.

3.5. Practical Implications for SMEs

The developed system provides practical advantages specifically for SMEs: (i) cost efficiency by leveraging readily available, low-cost components and open-source hardware/software (e.g., Arduino) commonly recommended for budget-constrained industrial IoT deployments [25]; (ii) ease of adoption, since open-source platforms lower vendor lock-in and reduce the need for specialized expertise critical where technical capacity is limited [26]; and (iii) scalability and flexibility through modular chamber sizing and sensor placement to accommodate diverse product geometries and drying requirements, aligned with modular low-cost process-control architectures [27]. For ceramic SMEs, compact IoT-enabled dryers have demonstrated improved process efficiency and monitoring accuracy under space/time constraints [28]. In manufacturing contexts, Open-Source Hardware further reduces entry costs and supports collaborative scaling, reinforcing replicability in resource-constrained settings [28].

Collectively, these features position the proposed system as a practical, adaptable, and replicable digital-manufacturing solution for ceramic drying.

4. Conclusion

This study demonstrated the successful design and optimization of an Arduino-controlled automatic ceramic drying system tailored for Small and Medium Enterprises (SMEs). Using a full factorial experimental design, the optimal configuration of 45°C temperature and 3 m/s airflow velocity was identified, achieving the shortest drying time of 18.031 seconds (300.5 minutes) with stable performance. Statistical analysis confirmed that temperature was the most dominant factor, contributing 78.87% of the variation, followed by airflow velocity at 15.84%, while the interaction effect was negligible. The robustness of the results was supported by SNR analysis and significant effect-size estimates, indicating both statistical and practical significance. Beyond numerical outcomes, the system offers practical value by providing a low-cost, scalable, and user-friendly solution that ceramic SMEs can easily adopt to reduce production time, minimize defects, and enhance product consistency. While the findings validate the potential of combining DoE with microcontroller-based automation for SME process improvement, future studies should consider larger-scale chambers, humidity regulation, IoT-based monitoring, and energy efficiency comparisons with industrial drying systems to broaden applicability and long-term sustainability.

Declaration of AI and AI assisted technologies in the writing process

In drafting this manuscript, the authors used ChatGPT for brainstorming and content structuring, and Grammarly for language refinement and grammatical accuracy. All output generated by these tools has been critically evaluated, revised, and verified by the authors. The authors take full responsibility for the integrity, accuracy, and originality of the final manuscript.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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