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Analysis of the effect of post-printing treatment of 3D Printer DLP machine for polylactic acid on surface hardness

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ABSTRACT

This study aims to determine the effects of factors and levels specifically, exposure times of 30 and 60 minutes; low and high spinning speeds; and washing times of 5 and 10 minutes on surface hardness using a 2^k full factorial design. Statistical analysis revealed that the Washing Time factor had a statistically significant effect on surface hardness with a P-value of 0.036 ($\alpha = 0.05$). Increasing the washing time from 5 to 10 minutes increased the mean surface hardness from 85.31 to 86.19 Shore D, or approximately 1.04%, indicating a statistically significant but modest practical effect within the tested experimental range. Meanwhile, the factors Exposure Time and Spinning Speed, as well as all interactions between the factors, did not have a statistically significant effect on surface hardness. The relatively low R^2 of 36.63% and predicted R^2 of 0.00% indicate that the model has limited explanatory and predictive capability.Residual analysis showed that the assumptions of normality and independence of the residuals were met. Overall, washing time showed a statistically significant but modest effect on surface hardness. Given the limited explanatory and predictive capability of the model, these findings should be interpreted only within the tested experimental range.

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1. INTRODUCTION

Digital Light Processing (DLP) is a 3D printing technology that operates on the principle of layer-by-layer manufacturing,capable of producing workpieces with complex shapes (Chaudhary et al. 2023; Putra et al. 2021; Shashi, Laskar, and Biswas 2017; Truxova et al. 2020), achieving high dimensional accuracy in printed

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results (Beyer et al. 2025; Palacio, Baniasadi, and Kardel 2023; Tatlicioglu et al. 2026),that technology continues to evolve (Lin, Liu, and Shin 2025), something not possible with conventional technologies (Truxova et al. 2020).

DLP 3D printing has been widely applied in fields such as healthcare, aerospace, education, construction, and defense (Adeleke et al. 2024; Al-Gawhari and Ali 2022; Pagac et al. 2021; Shashi et al. 2017; Tatlicioglu et al. 2026), and others. DLP technology shares similarities in its manufacturing process with the Stereolithography Apparatus (SLA), as both use photopolymerization to form workpieces (Al-Gawhari and Ali 2022; Chaudhary et al. 2023; Pagac et al. 2021).DLP technology uses conventional light sources such as arc lamps (Shashi et al. 2017), as well as an LCD (liquid crystal display) to generate a dynamic mask (Truxova et al. 2020). This technology was first introduced in 1987 (Shashi et al. 2017),and has continued to advance(Seprianto, Hidayat, and Ginting 2021).The material used in DLP 3D printers is a photopolymer (Chaudhary et al. 2023; Pagac et al. 2021), which comes in the form of resin (Marghitas et al. 2024). The post-processing of resin-based workpieces printed using photopolymerization-based 3D printing technology requires analysis, as this process affects the material's properties (Lassila et al. 2024; Nowacki et al. 2021; Štaffová et al. 2022).

One of the materials commonly used in 3D printing technology is polylactic acid, or PLA (Crisostomo and Dizon 2021). This material is widely used in various fields (Wang et al. 2024). For use in DLP 3D printers, PLA is available as a resin (Muflikhun 2025). Accordingly, information on its mechanical properties is necessary to tailor PLA-based products to specific application requirements(Arief et al. 2024; Nowacki et al. 2021). Therefore, an analysis of the post-printing process for this material is required to produce PLA prints with the desired mechanical properties. One such mechanical property is surface hardness. Surface hardness is the ability of a material's surface to resist pressure (Sulaeman. M, Budiman. H 2018). Evaluating the mechanical properties of 3D-printed specimens is important to determine whether the resulting parts meet the intended performance requirements. In this context, surface hardness is an important response for evaluating PLA-based printed specimens (Maguluri, Suresh, and Guntur 2022; Rosid et al. 2025). Research on post-printing treatments has been conducted by Nowacki et al. (2021). In that study, an analysis was performed on the effect of post-printing treatments using mSLA, with surface hardness (Shore D) as one of the test responses; however, no statistical analysis was conducted to determine the effect of the parameters used on the response. Research on PLA material with surface hardness as the response variable was also conducted by Rosid et al. (2025) using a 3D printer; however, that study employed an FDM-type 3D printer and a filament-based material. Meanwhile, in the study by Lassila et al. (2024), post-printing treatments were also applied to resin materials with surface hardness as the response variable, but dental materials were used.Taken together, these studies show that post-processing can affect the mechanical properties of 3D-printed materials; however, previous studies used different printing technologies, material types, or statistical approaches, limiting their direct applicability to PLA-based resin produced using DLP technology. However, the simultaneous main and interaction effects of post-curing exposure time, spinning speed, and washing time on the surface hardness of PLA-based resin manufactured by means of DLP technology have not been adequately examined. It is necessary to carry out a systematic assessment of the post-processing parameters in order to determine their influence on the final properties (Choi et al. 2022). That is why a 2^3 full factorial design was chosen since it allows the main and interaction effects of several factors to be evaluated at the same time, provided that the appropriate factors and factor levels are specified as experimental inputs (Pettalolo, Rosid, and Tontowi 2022; Rosid and Tontowi 2021). The novelty of this study is that it involves the simultaneous evaluation of these three post-processing factors and the interactions between them for PLA-based resin specimens produced using DLP technology. The aim of this study is therefore to establish the main and interaction effects of these post-processing parameters on the surface hardness of PLA specimens produced by means of DLP technology.

2. RESEARCH METHODS

The determination of the printing parameters was based on prior research on optimizing DLP 3D printer parameters for PLA. The parameters used, based on that research, were a layer height of 0.035 mm, an exposure time of 19.542 seconds, and a bottom exposure time of 60.679 seconds (Putra et al. 2021). The bottom layer count is set to 2, per the DLP printer's default settings. These DLP printing parameters were kept constant for all specimens and were not treated as experimental factors.

The machine used has a maximum print volume of 127x80x160 mm, a layer thickness ranging from 0.025 mm to 0.100 mm, and a print speed of 10 to 20 mm/hour (Figure 1a). The printing parameters for the DLP 3D printer are based on standard values, with a layer height of 0.035 mm, an exposure time of 19.542 seconds, and a bottom exposure time of 60.679 seconds (Wilza et al. 2019).

Figure 1.DLP 3D Printer (a) and Wash and Cure 3D Printer (b)

Surface hardness was measured using a Shore D durometer (American Society of Testing and Materials 2015). The Shore D durometer is intended for use with polymer materials in accordance with ASTM D2240 (Pratama and Adib 2022). Surface hardness was measured using a Shore D durometer with reference to ASTM D2240. Three measurements were taken at different positions on each specimen, and the average value was used as the surface hardness response.

The wash and cure machine used was the Creality UW-01, featuring UV LEDs with wavelengths of 385 nm and 405 nm, a washing volume of 170 x 120 x 160 mm, and a container volume of 4,500 ml (Figure 1b). The machine features 9 UV LEDs at a wavelength of 405 nm and 9 UV LEDs at a wavelength of 385 nm, with a washing area of 190 x 154 x 200 mm and a curing area of 200 x 300 mm. It utilizes a 360° rotating platform, with cure and wash durations ranging from 2 minutes to 90 minutes. The curing process involves irradiating the specimen with UV light at 385 nm, while the washing process involves cleaning it with IPA. The washing process uses the machine's default rotation speeds: low, medium, and high.

During the washing process, an alcohol-based solution is used to clean the specimen surface of resin residue resulting from the casting process (Hwangbo et al. 2021b; Nowacki et al. 2021). The material used for the washing process is 99% isopropyl alcohol (C_3H_7OH), or IPA, with "For Analysis" (FA) specifications, manufactured by Merck. IPA can be used as a washing liquid in the post-printing process for resin materials (Hwangbo et al. 2021b; Jang et al. 2021; Kang et al. 2024; Katheng et al. 2022; Liu et al. 2024; Truxova et al. 2020). As for the PLA material, eSun Bio PLA is used, with a wavelength of 395–405 nm, a density of 1.00–1.11 g/cm³, and a viscosity of 250–350 mPa·s.

The specimen was designed with dimensions of 60 × 30 × 6 mm (Figure 2). The specimen thickness of 6 mm satisfies the minimum thickness specified in ASTM D2240, while the lateral dimensions allow hardness measurements to be performed at an appropriate distance from the specimen edges. Computer Aided Design (CAD) was used to design the specimen, and the resulting 3 dimensional CAD model was then sliced. During the slicing stage, parameter settings were configured. After printing, the specimens were washed in 99% IPA according to the specified washing time and spinning speed for each experimental run. The washed specimens were then dried and subjected to UV post-curing according to the specified post-curing exposure time. Surface hardness was measured after completion of the post-processing procedure.

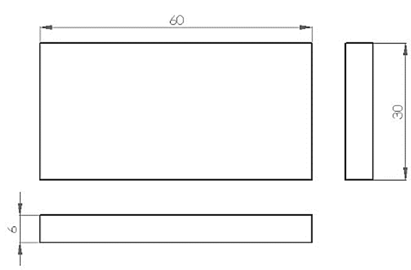

Figure 2.Specimen design

The experimental method used a 2^k full factorial design with three parameters, each having two levels. The 2^k full factorial design approach can be used as an experimental method to determine the optimal combination of parameters (Montgomery 2017; Rosid and Tontowi 2021). Statistical analysis was performed using Minitab 22 software. The 2^k full factorial design was used because it allows simultaneous evaluation of several factors, enabling more efficient identification of main and interaction effects than a one-factor experiment (Montgomery 2017). The Post-curing Exposure Time (PET) levels of 30 and 60 min were selected based on Nowacki et al. (2021). The Washing Time (WT) levels of 5 and 10 min were selected with reference to Hwangbo et al. (2021b), Katheng et al. (2022), and Nowacki et al. (2021). The Low and High levels of Spinning Speed (SS) were selected from the available default speed settings of the wash-and-cure machine (Table 1).The experimental factors evaluated in this study were post-processing parameters consisting of Post-curing Exposure Time (PET), Spinning Speed (SS), and Washing Time (WT). These factors were distinguished from the DLP printing parameters, which were maintained constant for all specimens

Table 1.Post-processing factors and factor levels

Parameter	Level		Unit	Ref.
	-1	1		
Post-curing Exposure Time	30	60	min.	(Nowacki et al. 2021)
Spinning Speed	180	550	-	default
Washing Time	5	10	min.	(Hwangbo et al. 2021b; Katheng et al. 2022; Nowacki et al. 2021)

The 2^3 full factorial design consisted of eight treatment combinations. Each combination was replicated three times, resulting in a total of 24 experimental runs (Table 2). For each experimental run, surface hardness was measured at three points on the specimen, and the average value was used as the response.

Table 2.Level values and printing parameters

Run Time	PET	SS	WT	PET	SS	WT
1	-1	-1	-1	30	Low	5
2	1	-1	-1	60	Low	5
3	-1	1	-1	30	High	5
4	1	1	-1	60	High	5
5	-1	-1	1	30	Low	10
6	1	-1	1	60	Low	10
7	-1	1	1	30	High	10
8	1	1	1	60	High	10
9	-1	-1	-1	30	Low	5
10	1	-1	-1	60	Low	5
11	-1	1	-1	30	High	5
12	1	1	-1	60	High	5
13	-1	-1	1	30	Low	10
14	1	-1	1	60	Low	10
15	-1	1	1	30	High	10
16	1	1	1	60	High	10
17	-1	-1	-1	30	Low	5
18	1	-1	-1	60	Low	5
19	-1	1	-1	30	High	5
20	1	1	-1	60	High	5
21	-1	-1	1	30	Low	10
22	1	-1	1	60	Low	10
23	-1	1	1	30	High	10
24	1	1	1	60	High	10

After the data were collected, an Analysis of Variance (ANOVA) was conducted to determine whether a factor or interaction had a significant effect on the response based on the F-value and P-value. The analysis procedure in Minitab included estimating factor effects, calculating standardized effects, and presenting the results visually via a Pareto chart of effects, a main effects plot, and an interaction plot, which helped facilitate an intuitive interpretation of the results. In addition, a check of the basic assumptions of ANOVA was performed to ensure that the model met the assumptions of normality, homogeneity of variances, and independence of errors. This entire series of analyses was conducted to ensure that the resulting factorial model was statistically valid and accurately represented the response behavior.

3. RESULTS AND DISCUSSION

The experimental results yielded surface hardness values for specimens molded under various combinations of parameters. The measurements revealed a maximum surface hardness value of 87.0 and a minimum value of 84.0 (Table 3).

Table 3. Experimental results

RT	*PET*	*SS*	*WT*	*Surface Hardness*			
				X1	X2	X3	X
1	30	Low	5	84	84	84	84.0
2	60	Low	5	84	85	86	85.0
3	30	High	5	84	85	85	84.7
4	60	High	5	86	86	86	86.0
5	30	Low	10	87	87	87	87.0
6	60	Low	10	86	85	85	85.3
7	30	High	10	87	87	87	87.0
8	60	High	10	86	86	86	86.0
9	30	Low	5	85	85	85	85.0
10	60	Low	5	84	84	84	84.0
11	30	High	5	84	84	84	84.0
12	60	High	5	87	86	87	86.7
13	30	Low	10	87	87	87	87.0
14	60	Low	10	87	86	87	86.7
15	30	High	10	85	85	85	85.0
16	60	High	10	86	85	85	85.3
17	30	Low	5	86	86	86	86.0
18	60	Low	5	87	87	87	87.0
19	30	High	5	86	86	86	86.0
20	60	High	5	86	85	85	85.3
21	30	Low	10	86	86	86	86.0
22	60	Low	10	87	87	87	87.0
23	30	High	10	86	86	86	86.0
24	60	High	10	86	86	86	86.0

For each runtime combination, the average response value was highest for the combination consisting of the PET factor at the low (-) level, the SS factor at the low (-) level, and the WT factor at the high (+) level. This combination yielded a response value (surface hardness) of 87 (Table 4).

Table 4. Response values for each combination

Comb.	PET	SS	WT	SH (Ave.)
1	-	-	-	85.00
2	+	-	-	85.33
3	-	+	-	84.89
4	+	+	-	86.00

5	-	-	+	86.67
6	+	-	+	86.33
7	-	+	+	86.00
8	+	+	+	85.78

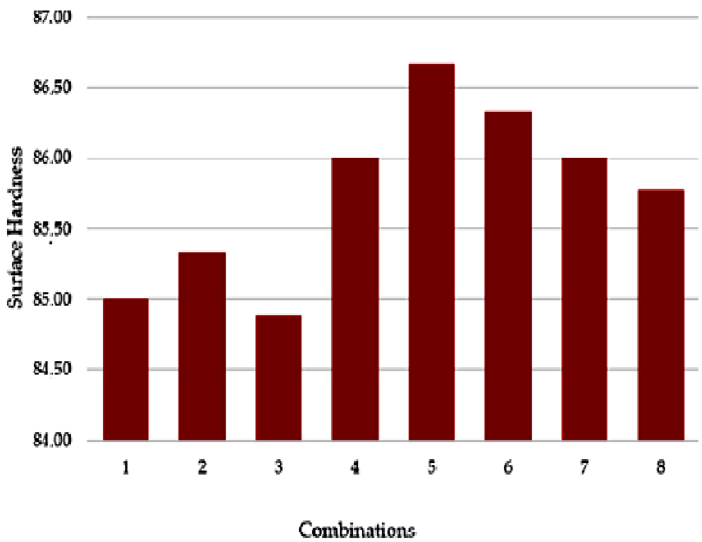

Figure 4. Surface Hardness test results for each combination

Descriptive analysis showed that the highest mean surface hardness within the tested experimental range was obtained at a PET of 30 min, low SS, and a WT of 10 min, corresponding to combination 5. The lowest mean surface hardness was obtained at a PET of 30 min, high SS, and a WT of 5 min, corresponding to combination 3 (Figure 4). Therefore, combination 5 should be considered the best-performing condition among the factor levels investigated in this study rather than a global optimum.Based on the model summary results, the R^2 value was 36.63%, the adjusted R^2 was 8.91%, and the predicted R^2 was 0.00%. The R^2 value of 36.63% indicates that the factors Exposure Time, Spinning Speed, Washing Time, and their interactions can explain 36.63% of the variation in surface hardness. Meanwhile, 63.37% of the variation in the response is attributed to other factors not analyzed in this study. The predicted R^2 of 0.00% indicates that the model has essentially no predictive capability for new observations. Therefore, the model should be used only to describe trends within the tested experimental range and not to predict surface hardness under new conditions (Table 5).

Table 5. Model summary

S	R-sq	R-sq(adj)	R-sq(pred)
0.946925	36.63%	8.91%	0.00%

The ANOVA results show that the Washing Time factor has a P-value of 0.036, which is less than the significance level of 0.05, while the Exposure Time and Spinning Speed factors have P-values of 0.583 and 0.672, respectively. Thus, Washing Time is the only main factor that has a significant effect on surface hardness at the 5% significance level. Meanwhile, the overall factorial model yielded an F-value of 1.32 and a P-value of 0.303, indicating that the model is not significant. The results of the two-factor interaction tests also showed P-values greater than 0.05: the interaction between Exposure Time and Spinning Speed was 0.583, between Exposure Time and Washing Time was 0.214, and between Spinning Speed and Washing Time was 0.261. This indicates that none of the two-factor interactions had a significant effect on surface hardness. Similarly, the three-factor interaction between Exposure Time, Spinning Speed, and Washing Time had a P-value of 0.672, indicating that it did not have a significant effect on surface hardness within the tested parameter range (Tab. 6).

Table 6. ANOVA

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	7	8.2933	1.1848	1.32	0.303

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Linear	3	5.1300	1.7100	1.91	0.169
PET	1	0.2817	0.2817	0.31	0.583
SS	1	0.1667	0.1667	0.19	0.672
WT	1	4.6817	4.6817	5.22	0.036
2-Way Interactions	3	2.9967	0.9989	1.11	0.373
PET*SS	1	0.2817	0.2817	0.31	0.583
PET*WT	1	1.5000	1.5000	1.67	0.214
SS*WT	1	1.2150	1.2150	1.36	0.261
3-Way Interactions	1	0.1667	0.1667	0.19	0.672
PET*SS*WT	1	0.1667	0.1667	0.19	0.672
Error	16	14.3467	0.8967		
Total	23	22.6400			

The regression coefficients describe the direction and magnitude of the estimated effects within the tested experimental range. Among the factors, WT showed the largest positive coefficient, while the coefficients of the other main and interaction effects were relatively small. However, these results should be interpreted with caution because the overall factorial model was not statistically significant (P = 0.303) and had limited predictive ability, as indicated by the predicted R^2 value of 0.00%. Therefore, the regression model is more appropriate for describing trends within the tested conditions than for predicting surface hardness outside the experimental range (Equation 1).

$$SH = 85{,}750 + 0{,}108\ PET - 0{,}083\ SS + 0{,}442\ WT + 0{,}108\ PET*SS - 0{,}250\ PET*WT - 0{,}225\ SS*WT - 0{,}083\ PET*SS*WT \quad (1)$$

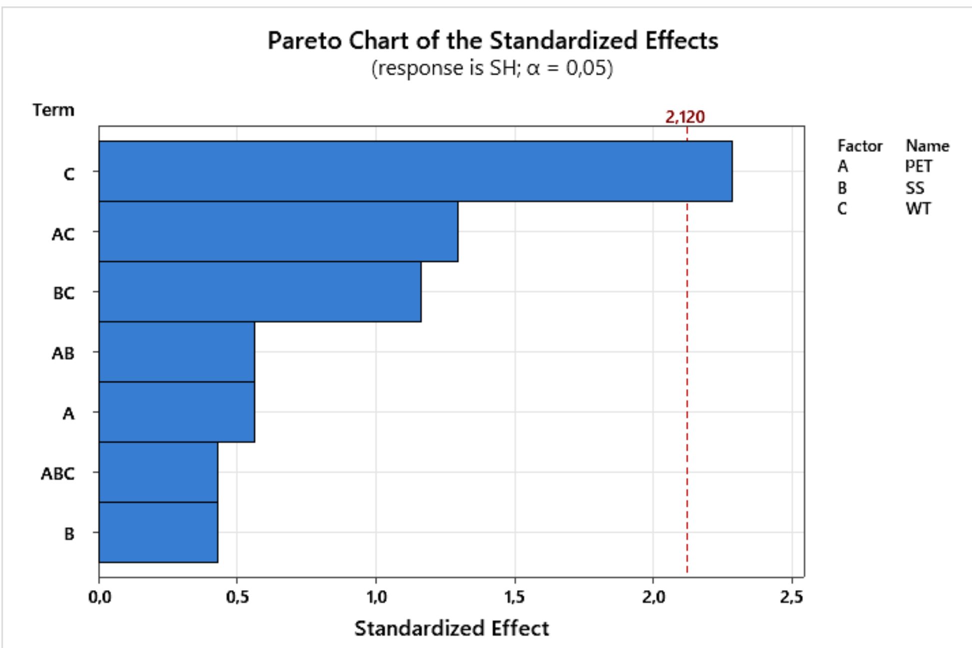

Figure 3. Pareto Chart of the Standardized Effects

The Pareto chart confirms that WT had the largest standardised effect on surface hardness, whereas the remaining main and interaction effects were relatively small (Figure 3).

Increasing the washing time from 5 to 10 min increased the mean surface hardness from 85.31 to 86.19 Shore D, corresponding to an increase of approximately 1.04%. Although statistically significant, this improvement was relatively small, indicating a modest practical effect. The increase may be associated with more effective removal of residual uncured resin from the specimen surface during washing. Previous studies have also reported that washing conditions can influence the mechanical properties and degree of conversion of photopolymer-based 3D-printed materials (Hwangbo et al. 2021a; Jang et al. 2021; Nowacki et al. 2021). However, because surface morphology and chemical conversion were not directly evaluated in this study, this mechanism should be considered a possible explanation rather than a confirmed mechanism. Meanwhile, the PET and SS factors did not show a statistically significant effect on surface hardness, either individually or through interactions between factors. In the regression analysis, an R^2 value of 36.63% indicates that the factors analyzed explain only a portion of the variation in the response. Although the residual analysis results show that the model's basic assumptions are met, the R^2, R^2 adj, and R^2-pred values indicate that the model's ability to explain and predict variations in surface hardness remains limited. Therefore, the model's results are only valid within the range of factors tested in this study.

4. CONCLUSION

Based on experimental results for PLA specimens produced with a DLP 3D printer, post-processing parameters had different effects on surface hardness. Washing Time (WT) was the only main factor that had a statistically significant effect on surface hardness, with a P-value of 0.036. Within the tested experimental range, increasing the washing time from 5 to 10 min was associated with an increase in the mean surface hardness from approximately 85.31 to 86.19 Shore D, corresponding to an increase of approximately 1.04%. Although statistically significant, this change was relatively modest and should therefore be interpreted cautiously. Post-curing Exposure Time (PET) and Spinning Speed (SS), as well as all two-way and three-way interactions, did not have statistically significant effects on surface hardness. The factorial model explained 36.63% of the variation in surface hardness, with an adjusted R^2 of 8.91% and a predicted R^2 of 0.00%. These values indicate that a substantial portion of the variation in surface hardness remains unexplained, possibly due to other printing, post-processing, material, or experimental factors that were not included in the present model. Therefore, the observed effect of washing time and the resulting parameter combination should be interpreted only within the experimental range evaluated in this study and should not be considered generally predictive beyond these conditions. Nevertheless, the results provide an initial indication of the role of post-processing parameters in determining the surface hardness of PLA specimens produced using DLP technology. Future studies should investigate additional printing and post-processing parameters, such as layer thickness, printing orientation, curing intensity, and washing conditions, to better explain the variation in surface hardness and develop a more robust predictive model.

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