

Experimental investigation of self-cleaning behaviour of 3D-printed textile fabrics with various printing parameters

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ABSTRACT

Self-cleaning of textile fabrics is defined as the ability that the pollutants particles can be removed from the fabric surface without any external source. The application of the technology is beneficial to the environment since it conserves water, energy and laundry costs. In the past, it is typically obtained by chemical coatings, which develop low surface energy and high roughness on the fabric surface, allowing the pollutant particles or droplets to float over the surface rather than adhesion. These chemical coating methods are effective for fabrics manufactured by traditional woven-based textile technology. However, the recent advancements in 3D printing technology have evolved the manufacturing of textile fabrics but with equal challenges in self-cleaning as previous chemical coating-based methods are not useful for printed fabrics. A recent study has successfully established a linear regression model to demonstrate the relationship between secondary 3D printing parameters and the self-cleaning properties of different polymeric fabrics. This paper is intended to analyse the impact of the primary printing parameters on the self-cleaning attributes, including infill rate (IR), flow rate (FR), printing temperature (PT), printing speed (PS), and printing acceleration (PA). The experimental results were used to construct a regression polynomial to quantify the self-cleaning behaviour of the selected thermoplastic polyurethane (TPU) fabric. The models were validated experimentally to highlight the critical values of considered primary parameters for optimal self-cleaning behaviour. The obtained results indicated that FR was the most significant parameter, and all parameters affected the fabric's wettability almost equally.

1. Introduction

The concept of self-cleaning property is to remove the pollutants particles from the textile fabric without another external source [1,2]. It is applied in textile fabrics to conserve laundry water and energy consumption. This feature can be achieved by developing a hydrophobic surface [3]. It is inspired by the lotus leaf effect, where liquid droplets carry the dirt particles and roll or slide off due to the low surface energy of the material [1–3]. The hydrophobic self-cleaning properties depend on the forces, including the interface force between the water-air interface and the particle, the adhesion force between the textile surface and the particle and the gravitational and buoyancy forces of the pollutant particles. It also depends on the wettability factor that represents the contact angle of the particle on the surface [2]. These forces and factors are also associated with microscopic features such as friction, adhesion, surface roughness and surface free energy [4]. The interdependencies between these forces and features are complex to

postulate and hence very challenging to quantify [2,4].

The recent advancement in 3D printing technology has revealed its potential for applications in the textile industry, especially with the perspective of self-cleaning [5]. Several studies comprehensively reviewed the recent progress of 3D printing for fabrics [6–9]. There are two forms of 3D printing applications for textiles [10], 3D printing on textile substrates [11–14] or 3D printing of textiles [15–19]. For the 3D printing of textiles, Partsch et al. investigated the textile properties of a 3D-printed acrylonitrile butadiene styrene (ABS) sample [20]. Forman et al. proposed a rapid and low-cost technique called DefeXtiles to produce tulle-like fabrics on unmodified fused deposition modelling (FDM) printers [21]. Takahashi and Kim listed some 3D-printed textile structures such as chainmail, weft knit and printed sheet [19]. The chainmail structure consists of tiny, interlocked parts that are flexible and customisable. The weft knit structure is knitted structure by 3D printing. The printed sheet investigated in this research means a 3D-printed single-layer or multi-layer mesh structure, which has been

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fabricated in some studies [21–23].

Among the 3D-printed textile, some fabrics require self-cleaning functionality for dust removal and waterproofing. For example, a recent study explored the potential applications of 3D-printed Thermoplastic polyurethane (TPU) mesh on tissue-support devices, such as ankle or knee braces [23]. Nike has also developed Nike Flyprint uppers via 3D printing TPU filament [6]. Therefore, it is significant to improve these 3D-printed fabrics' surface properties. In the existing literature, self-cleaning behaviours were achieved using chemical coatings on textile fabrics. However, the 3D-printed fabrics make it difficult to use conventional chemical coating methods to achieve self-cleaning behaviour [24–26]. Therefore, textile manufacturing has to consider another way, such as adjusting the printing parameters during the fabrication, to create textile fabrics with a self-cleaning feature.

The self-cleaning behaviours of FDM-based structures have been studied in the existing literature [27,28]. FDM printed part achieved a superhydrophobic surface with a silica nanoparticles dip coating [29]. Printing parameters and material properties of the used polymer were influential in developing such a surface [30–38]. The study showed that the increase in the infill density of the polyethylene terephthalate glycol (PETG) in FDM increases the specimen's tensile strength, reduces the surface roughness, and is less effective in generating self-cleaning behaviour [31]. Printing temperature, speed and flow rate demonstrated a decrease in the surface roughness and a slight increase in the porosity of polylactic acid (PLA) printed cubic parts [32]. Layer height, print temperature, print speed, print acceleration, and flow rate also obtained a non-pattern impact on the PETG printed rectangular specimen's surface roughness and wettability, with the flow rate and printing acceleration having the most significant influence [30].

Furthermore, a recent work developed a mathematical model of the FDM printing parameter such as layer thickness, orientation angle, and infill angle to the surface roughness of the ABS printed part using Response surface methods (RSM) [39]. Another study successfully used Taguchi Method and RSM for single and multi-objective optimisation and modelling construction for FDM printed PLA model. The optimised results suggested by the RSM models experimentally verified the Taguchi method's accuracy and the printing parameters' robustness [40].

However, all the above studies focused on 3D-printed structures rather than specific 3D-printed textile fabrics. Despite most published papers relevant to printed structures and self-cleaning behaviour at a surface level, the available literature still does not provide comprehensive quantitative insight to establish the interdependencies between the primary printing parameters and the mentioned behaviour. The authors recently established a linear regression model to demonstrate the quantitative relationship between secondary 3D printing parameters and the self-cleaning properties of different polymeric fabrics [41].

In authors' previous research, the influence of printing parameters on self-cleaning properties was analysed on three different materials, including Thermoplastic elastomer (TPE), TPU and Thermoplastic copolyester (TPC). A linear regression model was constructed and successfully optimised the secondary printing parameters of layer height, extruder width and angular orientation to obtain the optimised self-cleaning surface in terms of surface roughness, wettability, and porosity. The study further found that TPE has the best overall self-cleaning behaviour, followed by TPU and TPC [42]. However, the TPE was inconsistent during printing and resulted in poor-quality fabrics. It was concluded that TPU is more suitable than the other two materials. Therefore, in this paper, the impact of the primary 3D printing parameters on the self-cleaning behaviour of TPU is analysed only. Infill Rate (IR), Flow Rate (FR), Printing Temperature (PT), Printing Speed (PS), and Printing Accelerations (PA) are considered to be primary printing parameters in this paper. The experimental results are used to construct regression polynomials to quantify the self-cleaning of the selected fabric. The models were validated experimentally to highlight the critical values of considered primary parameters for optimal self-cleaning

behaviour.

The below-given description starts with a methodology, including details of specimen fabrication, design of experiments, experimental procedures, and measurements. Later, experimental findings are discussed, and mathematical modelling is explained to obtain an optimal self-cleaning behaviour of printed fabric.

2. Methodology

2.1. Specimen fabrication

The KODAK FLEX 98 TPU Filament was used for the printing in the tests. Critical technical data are listed in Table 1. The specimen geometry was designed as 100 mm × 60 mm × 0.3 mm to maintain consistency with the previous study [41]. The fabric model was designed with SolidWorks© 2021 and exported as an STL file. The file was imported to the printer ideaMaker© 4.2.0 software, as shown in Fig. 1(a) and Fig. 1(b), respectively. The optimal secondary printing parameters (i.e. 0.15 mm layer height, 0.5 mm extrusion width, 90° cross-raster orientation and 50 °C bed temperature) of the TPU fabric from the previous study were used. After slicing and setting parameters in the software, the g-code file was sent to Raise3D Pro 2 printer for fabrication.

2.2. Design of experiments

2.2.1. Printing parameter determination

Five primary printing parameters listed below were studied in the presented research because they significantly influence self-cleaning behaviour as per previous studies [41].

1. Infill Density (IF): The density of infill inside the structure. Since the specimen only had two layers without top and bottom layers, IF represented the relative distance between filaments in this study.
2. Printing speed (PS): The moving speed of the extruder to print
3. Printing Acceleration (PA): The moving acceleration of the extruder to print.
4. Printing Temperature (PT): The extruder's temperature.
5. Flow Rate (FR): Overall rate of the extruder to extrude the filament.

Each parameter was divided into three levels representing the upper value, the median and the lower value which were found by trial and error and summarised in Table 2. Fig. 2 shows three printed fabric textile samples, which were named after the run number and the printing order from bottom to top (1 is the bottom sample, and 3 is the top sample). The average strand distance of the printed specimens was around 0.2 mm.

2.2.2. Experimental scheme

Due to the complexity of the printing parameter variables and levels, there would be 3⁵ number of parameter combinations. Therefore, the Taguchi method was utilised to reduce the number of experiments. It used special orthogonal arrays to investigate all the experimental variables with minimum tests. A Taguchi L₂₇ orthogonal array shown in Table 3 was generated from the Design of Experiment software, Mini-tab®. It generated the 27 combinations of parameters required for the experiment. Three specimens were printed for each combination and

Table 1
KODAK FLEX 98 TPU technical data sheet [43].

Material properties		Recommended printer settings	
Tensile Strength (MPa)	57.9	Print temperature	(225 ± 5) °C
Tensile Elongation 100% (MPa)	19.3	Print bed temperature	70 °C First/ Later
Tensile Elongation 300% (MPa)	42.1	Cooling fans	Low/Off
Ultimate Elongation (%)	420	Adhesive	Required
Density (g/cm ³)	1.16	Closed environment	Not required

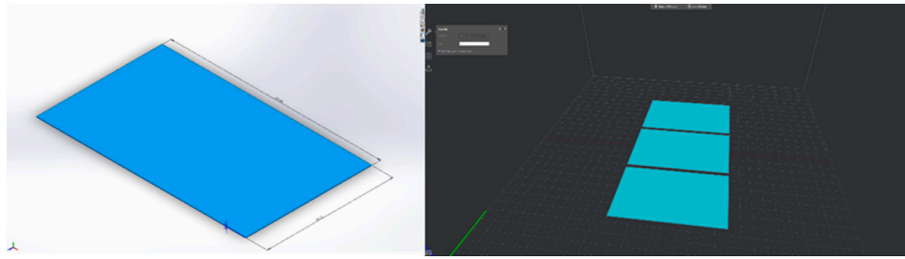


Fig. 1. (a) CAD model of the textile fabric sample (b) The preview of the printed samples in Idea Maker.

Table 2

Factors and levels of printing parameters.

Printing Parameter	Level 1	Level 2	Level 3
Infill Density (ID), %	15	50	100
Printing Speed (PS), mm/s	20	27.5	35
Printing Acceleration (PA), mm/s ²	200	500	800
Printing Temperature (PT), °C	235	240	245
Flow Rate (FR), %	90	120	150

tested to ensure the reproducibility of the results.

2.3. Experimental procedures and data process

The experiment flow and logic are shown in Fig. 3. The self-cleaning attributes and features of the specimens (porosity, surface roughness and contact angle) were examined, respectively.

The response results of each self-cleaning attribute were input to the Minitab software for determining the robustness of each parameter by calculating the Signal to Noise (S/N) ratio based on the two categories of performance characteristics, smaller-the-better and larger-the-better. As per our previous study, the ideal fabric would have minimum porosity and maximum contact angle. Hence, for the smaller-the-better variable, the S/N ratio can be calculated by Eq. (1), and for the larger-the-better variable, the S/N ratio can be calculated by Eq. (2), where n = the number of replications and Y represents the measurement data from the experiment.

$$\frac{S}{N} = -10 * \log_{10} \left(\frac{1}{n} \sum Y^2 \right) \quad (1)$$

$$\frac{S}{N} = -10 * \log_{10} \left(\frac{1}{n} \sum \frac{1}{Y^2} \right) \quad (2)$$

A mathematical model based on the RSM method was developed and used for optimisation by the response optimiser. RSM used

mathematical and statistical techniques to establish an adequate functional relationship between the response of interest and the control variables [44]. A second-order regression model, shown in Equation (3), was then used to fit the printing parameters and self-cleaning attributes.

$$y = b_0 + \sum_{i=1}^k b_i x_i + \sum_{i=1}^k b_{ii} x_i^2 + \sum_{i < j} b_{ij} x_i x_j + \epsilon \quad (3)$$

Where y is the response variable, b_0 is the constant, $b_1, b_2, \dots, b_k$ are the coefficients, $x_1, x_2, \dots, x_k$ are the control variables, ϵ is the error term. Minitab© calculated the individual desirability for each response result and weights each by its importance. The values were then combined to determine the composite desirability of the multi-response system. This led to generating the optimum solution when the desirability was the maximum. The mathematical model was further validated by printing the suggested optimised solutions and compared with the empirical results.

2.4. Self-cleaning attributes measurement

This subsection provides the details of the measurement of each self-cleaning attribute. The key measurands for self-cleaning attributes are Porosity (Po), Surface Roughness (Ra_0) and the Contact Angle (CA) as Wettability is evaluated by the CA .

2.4.1. Porosity measurement

For Po , a Dino-lite digital microscope was used to take the image of the fabric specimens. As shown in Fig. 4(a), the fabric sample was placed on top of a memo paper with a red mark area, and the image was taken from the DINO CAPTURE 2.0 with the change of contrast, saturation, hue, brightness, and sharpness setting to get a clear black and red image shown in Fig. 4 (b). The image was then converted to a binary image, as shown in Fig. 4 (c), which was used to calculate the total pores in the fabric by MATLAB©.

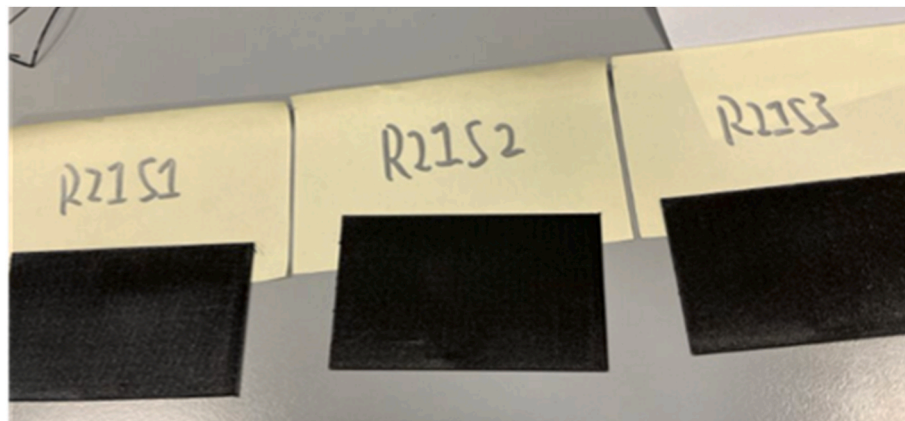


Fig. 2. The printed fabric textile samples.

Table 3

Experimental scheme designed by Taguchi L27 orthogonal array.

Run	IF (%)	PS (mm/s)	PA (mm/s ²)	PT (C°)	FR (%)
1	15	20	200	235	90
2	15	20	200	235	120
3	15	20	200	235	150
4	15	27.5	500	240	90
5	15	27.5	500	240	120
6	15	27.5	500	240	150
7	15	35	800	245	90
8	15	35	800	245	120
9	15	35	800	245	150
10	50	20	500	245	90
11	50	20	500	245	120
12	50	20	500	245	150
13	50	27.5	800	235	90
14	50	27.5	800	235	120
15	50	27.5	800	235	150
16	50	35	200	240	90
17	50	35	200	240	120
18	50	35	200	240	150
19	100	20	800	240	90
20	100	20	800	240	120
21	100	20	800	240	150
22	100	27.5	200	245	90
23	100	27.5	200	245	120
24	100	27.5	200	245	150
25	100	35	500	235	90
26	100	35	500	235	120
27	100	35	500	235	150

2.4.2. Surface roughness measurement

The Ra_0 were measured by the Taylor-Hobson profilometer. Specimens were first placed on the flat metal bed and held by a heavy metal object to prevent them from moving during the measurement, as shown in Fig. 5(a). Three measurements with the same setting were measured horizontally across the specimens' 10 mm × 10 mm centre region for consistent and reliable results, as shown in Fig. 5(b). Taylor-Hobson Ultra 6 software was used to control the profilometer and data capturing.

2.4.3. Contact angle measurement

The direct Goniometric Method was used to measure the CA. As shown in Fig. 6 (a), a water droplet was dropped from the syringe onto one of the samples, and an image was taken via the Ossila Contact angle application, as shown in Fig. 6 (b). The image can then be used for CA analysis as shown in Fig. 6 (c).

3. Results and discussion

The average results and their standard deviation (SD) of the 27 Runs with three samples each are shown in Table 4. Although all three parameters were the dependent variables of the experiment, the correlation between them was assessed in this study, as a large number of previous research have pointed to the influence of Ra_0 on CA [45,46]. However, the p-values of the Pearson correlation coefficient between

CA/ Ra_0 and CA/ Po were 0.15 and 0.37, respectively. Both values were over 0.05, which means there is no significant correlation. The potential reasons for this are the combined influence of printing parameters. This anomaly warrants a more in-depth study in the future.

The detailed results and analysis of each microscopic self-cleaning feature will be discussed in the following sub-section. The robustness of each printing parameter was investigated based on the S/N ratio to rank them.

3.1. The influence of printing parameters on porosity

As the porosity determines the size and number of the holes within the textile fabric, hence it is desired to be as low as possible. Table 5 shows the S/N ratio for porosity and rankings of each printing parameter. It indicates that FR is the dominant influential parameter to the Po as the difference between the highest and lowest average Po , delta, as large as 12.96. Fig. 7 further illustrates the significant influences of the FR between each level. However, it is worth mentioning that level 2 values yield maxima or minima within an insignificant range for other printing parameters. These tendencies require further investigation. The optimal parameters setting for the smallest Po are those levels with the lowest value, i.e., ID = 100%, PS = 20 mm/s, PA = 500 mm/s², PT = 245°, FR = 150%.

3.2. The influence of printing parameters on surface roughness

The Surface Roughness has a significant impact on the CA of hydrophobic material and hence its wettability. The higher value of, the higher CA of the droplet [42,47]. It is therefore desired to be as high as possible. Table 6 indicates that FR is the dominant influential parameter to the Ra_0 as the delta value is as large as 4.59. Followed by PT. Fig. 8

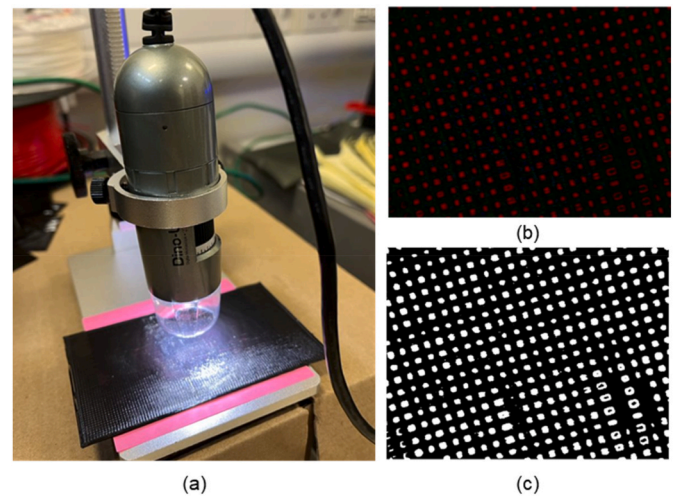


Fig. 4. (a) Fabric under the Dino-lite microscope with LED (b) Image taken from Dino-lite application (c) Binary image converted by MATLAB.

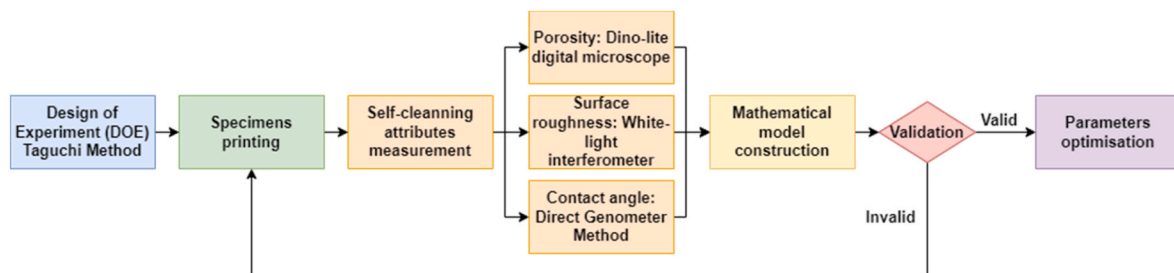


Fig. 3. The experiment flow and logic block diagram.

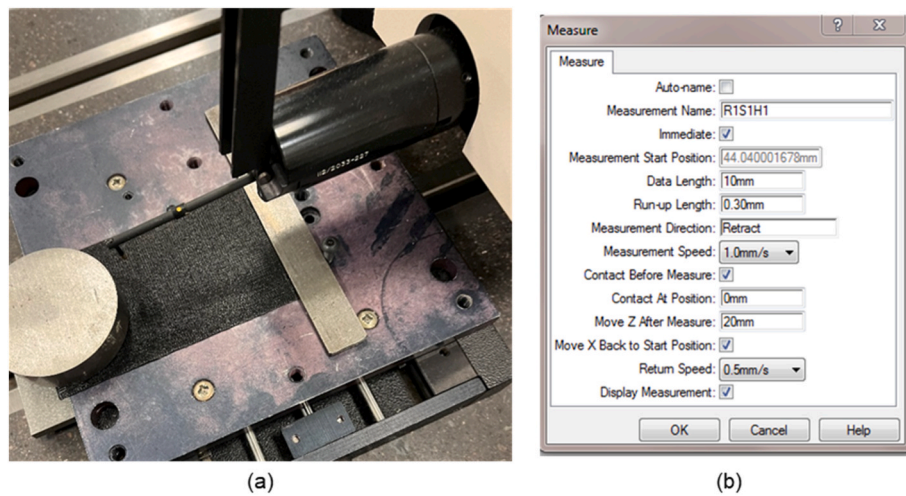


Fig. 5. (a) Specimen measured with the Taylor-Hobson profilometer (b) Taylor-Hobson Ultra software measurement setting.

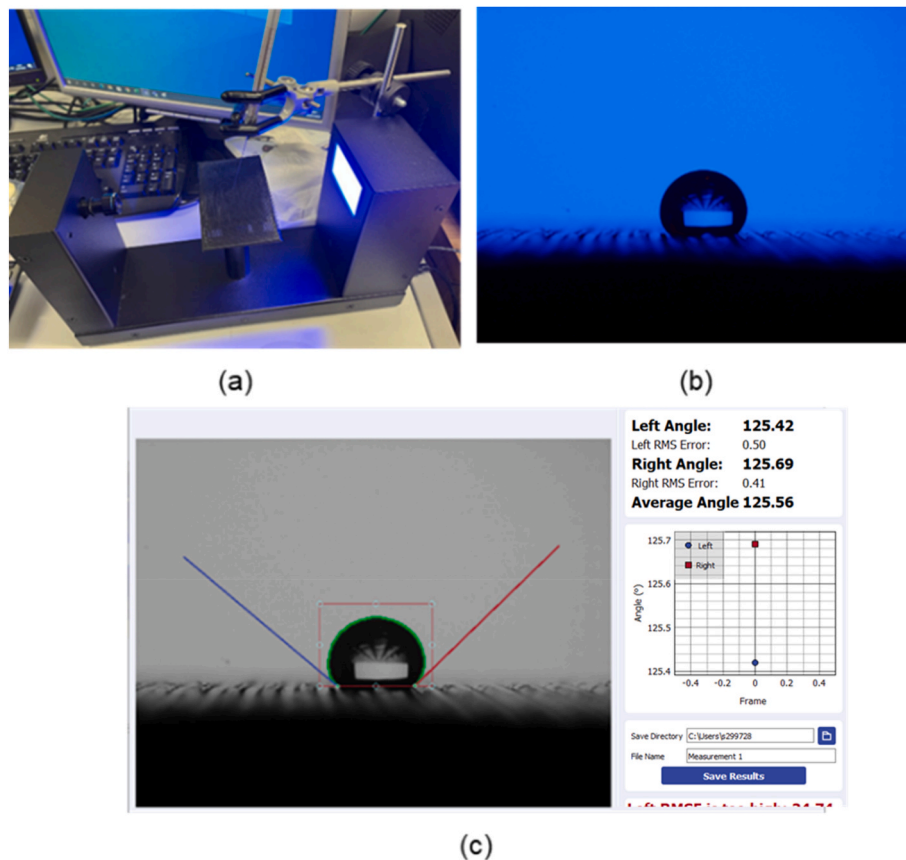


Fig. 6. (a) Ossila Contact Angle Goniometer setup (b) Image of a water droplet on the fabric taken from the Ossila Contact Angle application (c) Image of CA analysis by the Ossila Contact Angle application.

shows the dramatic drop of Ra_0 as the FR increase, whereas Ra_0 is first increases notably when PT increases and slightly drops after. The optimal parameters setting for the largest Ra_0 are those levels with the highest value. i.e., ID = 0%, PS = 20 mm/s, PA = 200 mm/s², PT = 240°, FR = 90%.

3.3. The influence of printing parameters on contact angle

As the higher CA means the poor wettability of the material and hence the better hydrophobicity, thus, the fabric is desired to have as

large CA as possible. Table 7 indicates that the highest influential parameter is FR (delta = 0.56), followed by PA (delta = 0.30). PS, ID and PT have a similar influence on CA as their delta value is about the same. Fig. 9 further supports this as it illustrates that FR fluctuated dramatically as it changed the level, followed by PA. PS, ID and PT have similar changes. The optimal parameters setting for the largest CA are those levels with the highest value. i.e., ID = 50%, PS = 35 mm/s, PA = 200 mm/s², PT = 240°, FR = 120%.

Table 4

Average self-cleaning attributes results of Taguchi L27 orthogonal array.

Run	CA (°)		Ra ₀ (μm)		Po (%)	
	Mean	SD	Mean	SD	Mean	SD
1	126.59	4.71	11.05	0.18	24.86	0.15
2	133.16	1.82	8.26	0.54	16.05	1.91
3	119.40	2.37	5.52	0.78	5.04	0.72
4	126.65	3.28	11.70	0.22	26.46	0.49
5	133.28	2.02	8.27	0.48	15.88	1.25
6	115.99	6.12	5.91	0.27	6.56	1.62
7	128.63	1.40	10.93	0.30	25.82	0.35
8	130.24	1.25	8.19	0.58	12.89	2.59
9	126.62	1.01	4.91	1.09	4.09	0.67
10	121.04	0.76	11.24	0.43	23.36	0.36
11	129.07	4.35	9.10	1.26	5.45	0.37
12	127.02	3.48	5.32	1.06	2.01	0.42
13	128.15	1.22	8.91	0.93	22.27	0.80
14	130.19	1.01	7.92	0.33	17.03	0.63
15	125.27	1.16	5.75	0.99	8.61	0.55
16	131.51	2.79	11.47	0.45	31.43	0.28
17	136.78	0.34	8.91	0.16	19.12	0.21
18	131.77	2.68	5.84	0.26	9.48	1.24
19	125.79	1.72	11.25	0.30	22.07	0.18
20	131.42	1.70	9.29	0.43	12.66	0.74
21	121.59	9.73	6.42	0.25	5.04	1.16
22	124.98	5.25	11.34	0.47	24.26	0.49
23	131.48	0.70	9.56	0.30	11.71	0.95
24	129.79	2.21	6.64	0.34	5.84	0.46
25	127.17	3.81	5.20	0.36	12.54	1.28
26	130.71	1.87	6.54	0.44	10.20	0.65
27	115.76	4.11	7.60	0.51	4.19	0.55

Table 5

Response Table for Signal to Noise Ratios for Porosity, Smaller is Better.

Level	ID	PS	PA	PT	FR
1	-21.95	-19.69	-22.84	-21.21	-27.27
2	-21.51	-22.61	-19.06	-22.99	-22.10
3	-20.22	-21.37	-21.77	-19.47	-14.30
Delta	1.73	2.92	3.78	3.52	12.96
Rank	5	4	2	3	1

3.4. Printing parameters robustness discussion

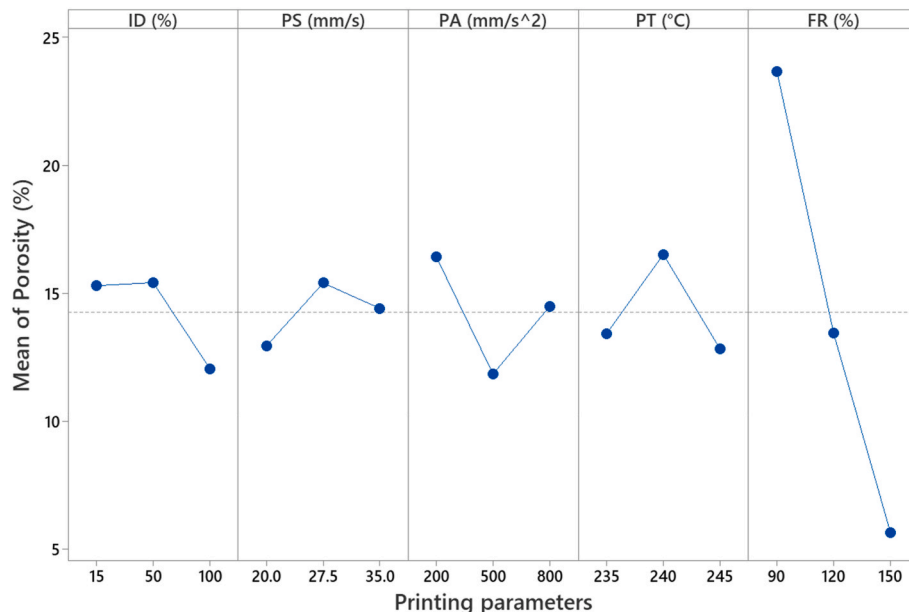
From the results obtained, the significant finding was that the dominant influential printing parameter was the FR, followed by PA and PT. This was somewhat close to the previous works [30,31,48]. A simple explanation for the FR being the dominant influential printing parameter in Po and Ra_0 was that the excess filament pressed by the nozzle head flowed to the surrounding. As a result, they filled the gap between the printed filament line and decreased the height difference between the first and second layers. For the same reason, CA was increased significantly first as smaller Po means the water droplet contact with a larger horizontal surface area of the hydrophobic TPU material. It was then decreased dramatically as the effect of the Ra_0 starting to kick in where the water droplet contacted a smaller vertical surface area. The effect of PA on the geometry of the filament has been studied and can be explained in Fig. 10. High PA reduced the acceleration and deceleration zone and gave a consistent deposited filament line. Thus, the gap between each filament was reduced and decreased in Po . This was until the nozzle head getting over accelerated and decelerated that making the filament unstable, detached from the printing bed and starting to fuse with the filament. The void between filaments was therefore increased, leading to high Po . This can be observed in the $PA = 800 \text{ mm/s}^2$ run samples, as shown in Fig. 11.

The above explanation of FR influencing CA demonstrated the complex relationship between CA, Ra_0 and Po . This corresponds to the finding of [2,4]. As Ra_0 and Po had their own printing parameter contributors (see Tables 5 and 6), it was therefore expected that all the studied printing parameters influence as much as each other on CA. The hypothesis was supported by experimental results in Table 7, which showed the delta value of each factor not greater than 0.56 and as close

Table 6

Response Table for Signal to Noise Ratios for Surface Roughness, Larger is Better.

Level	ID	PS	PA	PT	FR
1	18.01	18.37	18.52	17.16	20.07
2	18.05	18.27	17.57	18.58	18.49
3	17.99	17.40	17.95	18.30	15.48
Delta	0.05	0.96	0.95	1.42	4.59
Rank	5	3	4	2	1

**Fig. 7.** Main effects plot for means for porosity.

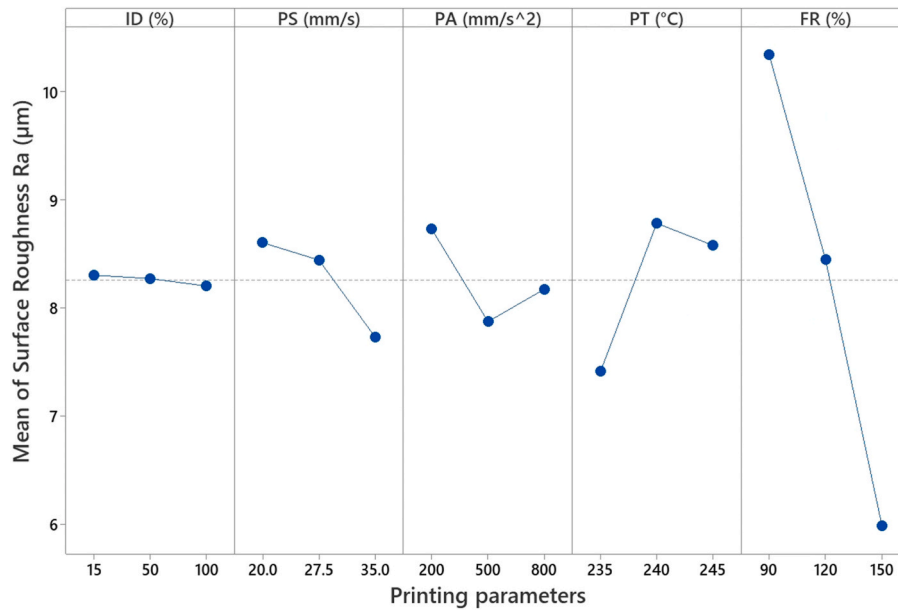


Fig. 8. Main effects plot for means for surface roughness.

Table 7

Response Table for Signal to Noise Ratios for Contact Angle, Larger is Better.

Level	ID	PS	PA	PT	FR
1	42.05	42.01	42.24	42.02	42.06
2	42.21	42.09	41.94	42.16	42.40
3	42.04	42.19	42.11	42.12	41.84
Delta	0.17	0.18	0.30	0.14	0.56
Rank	4	3	2	5	1

as 0.2.

3.5. Mathematical modelling and optimisation

A second-degree polynomial RSM model was applied in Minitab to determine the regression model and correlation of input parameters

with the response. Each input parameter has the unit as same as in Table 2. The regression model of each self-cleaning attribute feature is given in Equations (4)–(6). It is worth noting that each regression coefficient has its own unit based on its relations with self-cleaning properties. However, the research did not compare the coefficient magnitudes, so their units are not presented here.

$$\begin{aligned}
 Po (\%) = & -8057 - 0.0803ID + 1.502PS - 0.0519PA + 66.5PT + 1.85FR \\
 & - 0.000697ID^2 - 0.0305PS^2 + 0.00004PA^2 - 0.136PT^2 + 0.001356FR^2 \\
 & + 0.000981ID * FR + 0.00228PS * FR + 0.000072PA * FR \\
 & - 0.01092PT * FR \\
 = & \mathbf{96.93\%}
 \end{aligned}$$

(4)

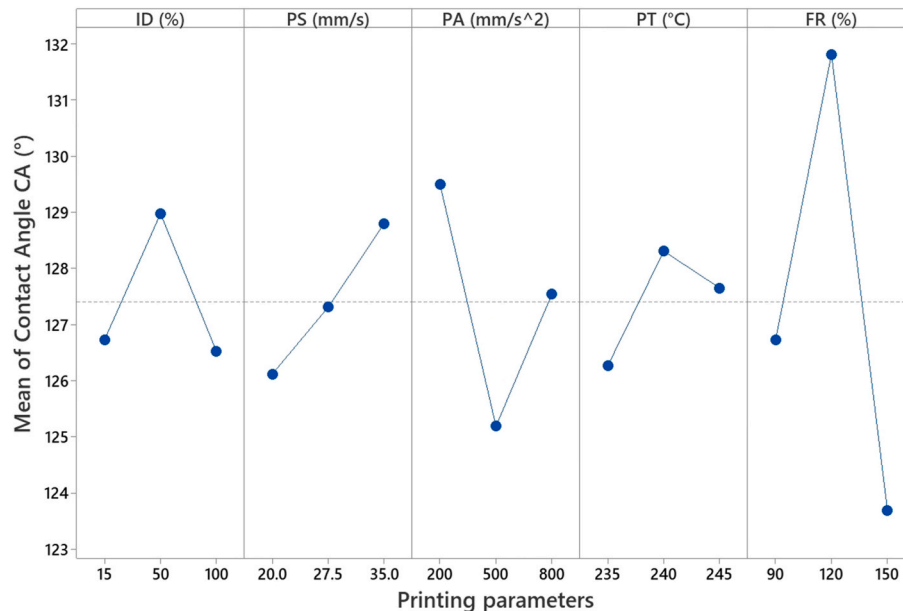


Fig. 9. Main effects plot for means for contact angle.

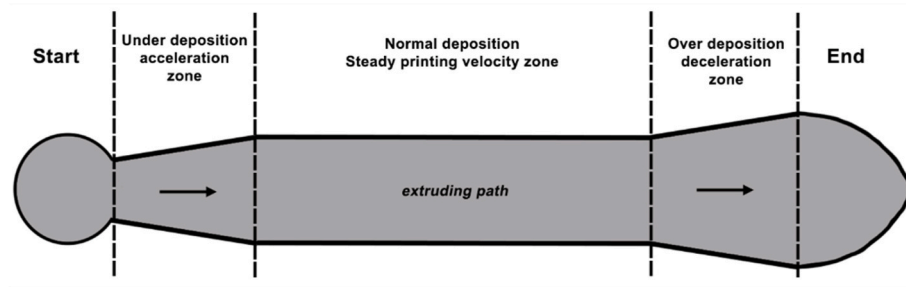


Fig. 10. Illustration of geometry extruding errors from start to end (elaborated from Ref. [49]).

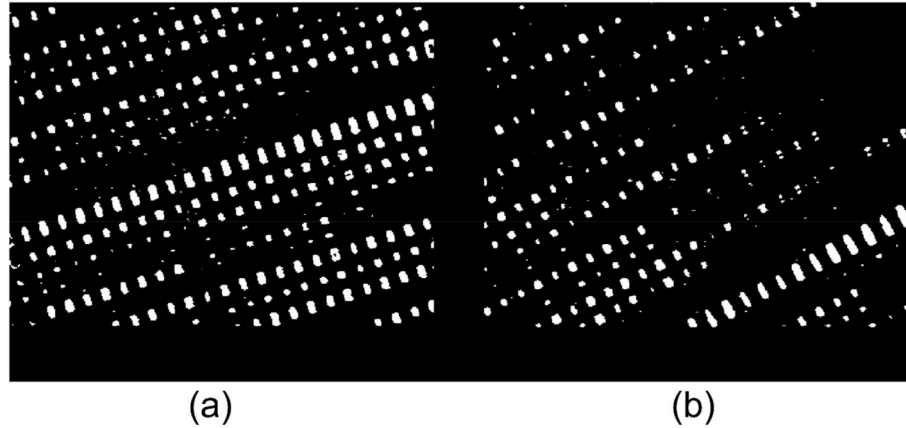


Fig. 11. Converted binary images from raw images under Dino-lite microscope of (a) Run8 and (b) Run14 (white area represents the porosity).

$$\begin{aligned}
 CA (^{\circ}) = & -2630 + 0.0317 ID + 0.38 PS - 0.0325 PA + 24 PT - 2.24 FR \\
 & - 0.000941 ID^2 + 0.0027 PS^2 + 0.000037 PA^2 - 0.054 PT^2 \\
 & - 0.00734 FR^2 + 0.000503 ID * FR - 0.00287 PS * FR - 0.000065 PA \\
 & * FR + 0.01682 PT * FR R^2 \\
 = & \mathbf{82.95\%}
 \end{aligned}$$

(5)

Table 8

Optimising solution and results prediction of the fabric textile.

Solution	ID (%)	PS (mm/s)	PA (mm/s ²)	PT (C°)	FR (%)	Composite Desirability
1	85	20	200	245	120	0.72

$$\begin{aligned}
 Ra_0 (\mu m) = & -1980 - 0.0683 ID - 0.1PS - 0.00938 PA + 15.91 PT + 1.277 FR - 0.000008 ID^2 - 0.00493 PS^2 + 0.000006 PA^2 - 0.0315 PT^2 \\
 & - 0.000315 FR^2 + 0.000568 ID * FR + 0.0026 PS * FR + 0.000017 PA * FR - 0.00576 PT * FR R^2 = \mathbf{94.20\%}
 \end{aligned}$$

(6)

It is shown that the models covered all the data comprehensively and are applicable to represent the correlations between the printing parameters and the self-cleaning attributes features significantly as the R-squared (R^2) are 96.93%, 82.95% and 94.20%, respectively. These high R-squared values indicated that most of the variation of self-cleaning properties could be explained by the printing parameters in proposed regression polynomials.

The response optimiser that is maximising Ra_0 and CA while minimising Po is then applied in Minitab to determine the optimising solution by compromising. The solution with the highest composite desirability is shown in Table 8.

3.6. Mathematical model validation and discussion

Three fabrics following the optimising solution in Table 8 are printed. The observed results, the predicted result from the RSM regression model and the Standard Error of Estimate (S_e) are shown in Table 9. The

Table 9

Table of the experimental results and predicted results of the validation samples.

	Sample 1	Sample 2	Sample 3	Regression Model Prediction	S_e
CA, °	132.68	132.84	133.78	133.2	0.495046
Ra_0 , μm	10.5	10.43	10.24	9.55	0.842204
Po, %	11.22	11.91	11.99	12.05	0.485652

Table 10

Model summary of each self-cleaning features model.

Model	S, unit	R^2 , %	$R^2(adj)$, %	$R^2(pred)$, %
CA	3.11°	82.95	63.07	12.42
Ra_0	0.08 μm	94.2	87.44	61.43
Po	2.18%	96.93	93.35	85.05

models' validity and accuracy are generally acceptable because the results validate the regression model as the S_e of each model is less than 1. Moreover, the model also successfully gives a multi-objective optimised solution.

Furthermore, Table 10 shows the statistical summary of each self-cleaning features model. It is worth noting that CA model has a very poor predictive ability as the $R^2(pred) = 12.42\%$. This might be due to the complexity of the interrelationship, which is explained in Section 3.4. Another reason is that since Minitab used the data from the Taguchi array, the interaction effects of some printing parameters were skipped, which are required for RSM. It is therefore suggested to improve the model predictivity by filling in the missing data experimentally.

4. Conclusion

The present research aimed to empirically investigate the influence of 3D printing parameters (Infill Density, Printing Speed, Printing Acceleration, Printing Temperature and Flow Rate) on the critical self-cleaning attribute features (Wettability, Surface Roughness, Porosity) of the FDM TPU textile fabric. This study has been one of the first attempts to thoroughly examine the self-cleaning properties of FDM fabric textiles.

From the results obtained, it is found that the dominant influential printing parameter is the Flow Rate, followed by Printing Acceleration and Printing Temperature. The results further suggest that all the printing parameters influence the fabric's wettability almost equally. These results contribute to understanding the printing parameter's influence on self-cleaning behaviours. Before this study, only the surface roughness of FDM structures was investigated, but this paper provided a deeper insight into several self-cleaning properties with a comprehensive investigation of some primary printing parameters.

Furthermore, a validated and accurate mathematical model for each cleaning attribute feature was also established by RSM. The models successfully provided an optimal solution with maximised contact angle and surface roughness while minimising the porosity, giving the best self-cleaning ability. This model may be of assistance in promoting the application of FDM self-cleaning fabrics in the textile industry.

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Author statement

Ka Po Chan: Methodology, Software, Validation, Formal analysis, Investigation, Data Curation, Writing - Original Draft, Visualization. **Feiyang He:** Software, Validation, Writing - Review & Editing, Visualization. **Ayat Adnan Atwah:** Methodology, Software. **Muhammad Khan:** Conceptualization, Methodology, Resources, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

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.

Data availability

Data will be made available on request.

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