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Optimisation Of Air Atmospheric Pressure Plasma Jet treated Cyclic Olefin Polymer Surface

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ABSTRACT

Low-temperature atmospheric-pressure plasma jets (APPJ) are increasingly used in surface activation, cleaning, wound care, and sterilisation applications. The development of successful applications using these systems requires the ability to tailor the active species generated by the plasma jets to match the treatment requirements. One of the most common applications of APPJ is surface modification of polymers, altering the nature of hydrophilicity Polymers surface to hydrophobic, many researchers investigated physical and chemical behavior during and after plasma treatment. In this paper, another study conducted using the Design Expert V12 software identified the optimal conditions for APPJ in order to increase productivity and minimize overall operating costs. Graphs were plotted by applying the contours to the different response surfaces. The effect of the process parameters was determined and the optimal operating conditions of the plasma were presented. This paper presents an optimising of the effect of APPJ on the cyclic olefin polymers (COPs) especially there is no previous studies dealed with the plasma treating poymers optimization. The historical data involving the D-optimal criterion was used for the optimisation of the process. The effect of plasma parameters such as input voltage, plasma power supply frequency, air flow rate, and distance between the plasma jet nozzle and cyclic olefin poymer (COP) surface were investigated. According to the analysis of variance (ANOVA) results, the proposed model can be used to navigate the surface wettability very well. The optimum operating condition for obtaining the lowest water contact angle was predicted. The results showed that the COP surface modification is affected by all the parameters studied, but it is most sensitive to plasma frequency, distance, and air flow rate.

Keywords: Atmospheric pressure plasma jet, wettability, Cost, Optimisation, Design Expert.

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الملخص

تستخدم نفاثات البلازما ذات الضغط الجوي المنخفض (APPJ) بشكل متزايد في تنشيط السطح ، والتنظيف ، والعناية بالجروح ، وتطبيقات التعقيم. يتطلب تطوير التطبيقات الناجحة باستخدام هذه الأنظمة القدرة على تكييف الأنواع النشطة التي تولدها نفاثات البلازما لتتناسب مع متطلبات العلاج. أحد أكثر تطبيقات APPJ شيوعًا هو تعديل سطح البوليمرات ، وتغيير طبيعة سطح البوليمرات المحبة للماء إلى مسعور ، قام العديد من الباحثين بالتحقيق في السلوك الفيزيائي والكيميائي أثناء وبعد العلاج بالبلازما. في هذا البحث ، حددت دراسة أخرى أجريت باستخدام برنامج Design Expert V12 الظروف المثلى لـ APPJ من أجل زيادة الإنتاجية وتقليل تكاليف التشغيل الإجمالية. تم رسم الرسوم البيانية من خلال تطبيق الخطوط العريضة على أسطح الاستجابة المختلفة. تم تحديد تأثير معاملات العملية وعرض ظروف التشغيل المثلى للبلازما. يقدم هذا البحث تحسينًا لتأثير APPJ على بوليمرات الأوليفين الحلقية (COPs) خاصةً أنه لا توجد دراسات سابقة تعاملت مع تحسين معالجة البويمر بالبلازما. تم استخدام البيانات التاريخية التي تتضمن معيار -D الأمثل لتحسين العملية. تأثير معلمات البلازما مثل جهد الدخل ، تم فحص تردد إمداد طاقة البلازما ، ومعدل تدفق الهواء ، والمسافة بين فوهة نفاثة البلازما وسطح بويمر الأوليفين الدوري .(COP) وفقًا لتحليل نتائج التباين (ANOVA) ، يمكن استخدام النموذج المقترح للتنقل في قابلية ترطيب السطح جيدًا. تم التنبؤ بحالة التشغيل المثلى للحصول على أدنى زاوية ملامسة للماء. أظهرت النتائج أن تعديل سطح COP يتأثر بجميع المعلمات المدروسة ، ولكنه الأكثر حساسية لتردد البلازما ، والمسافة ، ومعدل تدفق الهواء.

الكلمات المفتاحية : نفاثة بلازما للضغط الجوي ، قابلية البلل ، التكلفة ، التحسين ، خبير التصميم.

1 Introduction

Low-temperature atmospheric-pressure plasma jet (APPJ) are being increasingly used in (Chen & Li, 2015)surface activation, cleaning, wound care, and sterilization applications. The development of successful applications using these systems depends on the ability to tailor the active species generated in the plasma jets to match the treatment requirements. This paper presents an optimising of the effect of APPJ on the cyclic olefin polymers (COPs). Surface wettability of COP were correlated with water contact angle geometry. the historical data involving D-optimal criterion was used for the optimization of the process. The effect of plasma parameters such as input voltage, plasma power supply frequency, air flow rate, and distance between the nozzle on COP surface were investigated. According to analysis of variance (ANOVA) results, the proposed model can be used to navigate the surface wettability very well. The optimum operation condition for obtaining the lowest water contact angle was predicted. The results showed that the COP surface modification is affected by all the parameters studied but it is mostly sensitive to plasma frequency and distance and air flow rate.

Many studies have been carried out over the years, using techniques that could be used for materials that were traditionally unviable for microfluidic devices. Due to its excellent optical, mechanistic, chemical resistance, low water absorption and low cost, Cyclic Olefin Polymers (COPs) are ideal for microfluidic applications. Conventionally, the materials employed in the microfluidic devices are generally hydrophobic and the cyclic olefin polymer surface is hydrophilic, there are various techniques used to gain hydrophilic surfaces which include wet-chemical etching (Park, Meresa, Kwon, & Kim, 2019), corona discharges (Hansen, Finlayson, Castille, & Goins, 1993; ul Haq, Boyd, Acheson, McLaughlin, & Meenan, 2019), laser irradiation (Wang, Wang, Zheng, & Lam, 2015), ion beam treatment (Agulló-López, Climent-Font, Muñoz-Martín, Olivares, & Zucchiatti, 2016) and plasma treatment (Kim, Lee, Mishra, & Yeom, 2016). In this paper, we have chosen air atmospheric pressure plasma jet (APPJ) approach for COP surface modification as a result of many advantages, they can produce many reactive species which have a great impact on surface factualisation, in addition to reduction in the low cost of equipment and operation, low temperature processes resulting low surface damage, furthermore, they can be used for treat microfluidic channel (Yamasaki, Terao, Suzuki, Simokawa, & Takao, 2013). It is very convenient approach for modifying surface functional groups without affecting bulk properties (Kostov, Nishime, Castro, Toth, & Hein, Luis Rogerio de Oliveira, 2014). The fabrication of polymeric material for microfluidics applications, such as cyclic olefin polymers (COP), can be achieved by atmospheric pressure plasma jet by nanoscale surface etching (Kim et al., 2016; Vesel & Semenic, 2012) and surface functionality (Merenda et al., 2016; ul Haq et al., 2019).

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Functional surfaces have a great significance in polymers surface fabrication spatially increasing its low surface energy (Shenton, Lovell-Hoare, & Stevens, 2001) as they can enhanced wettability of their surfaces. Increased hydrophilicity of the COP. The APPJ operating conditions have a critical impact on polymers surfaces modification (Dowling, O'Neill, Langlais, & Law, 2011). In this paper, we studied the optimization of APPJ parameters such as input voltage (V), power supply frequency (kHz), gas flow rate (l/min) and jet to substrate distance (mm) on the COP surface wettability which measure wate contact angle. Furthermore, the sample treatment cost has been calculated to achieve a compromise between the quality (low water contact angle) and the quantity (low cost).
Therefore, this paper firstly aims to employ the historical data design to relate the Atmospheric pressure plasma jet input parameters to the two responses (water contact angle and operating cost). The second aim is to find the optimal factors combination that would maximize the water contact angle while keeping the cost relatively low. The APPJ parameters used in this study were selected as they are the only parameters that can be controlled on the APPJ equipment used.

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2 METHODOLOGY

2.1 Response surface methodology

Engineers often want to define the values of the input process parameters, at which the answers are optimally obtained. In terms of the process input parameters the best may be either a minimum or a maximum of a certain function. design of Experiment is one of the currently commonly used optimization techniques to explain the atmospheric pressure plasma jet modified polymers surface efficiency and to find optimal responses. This design is a series of techniques for predicting the interest response affecting a variety of input variables, which are useful in optimizing this response (Lohr, 2019). This design also defines the relationships and the controllable variables of inputs between one or more assessed responses (Khuri & Cornell, 2018). If all independent variables in experiments with negligible errors are observable, regulated, and continuous, the response surface can be expressed.by equation (1-3).

$$y = f(\, x_1, x_2, x_3, \dots\dots\dots, x_k \,) \quad . \qquad (1\text{-}3)$$

where k is the number of independent variables.
In order to optimize the" y" response, the true functional relationship between independent variables and the response surface must be accurately approximated. Typically, a second-order polynomial Eq. (2-3) is used in historical data.

$$y = b_0 + \sum b_i x_i + \sum b_{ii} x^2{}_{ii} + \sum b_{ij} x_i\, x_j + \varepsilon \quad . \qquad (2\text{-}3)$$

where k is the number of independent variables.
In order to optimize the "y" response, the true functional relationship between independent variables and the response surface must be accurately approximated. Typically, a second-order polynomial Eq. (2-3) is used in design of Experiment.

2.1.1 Experimental design

2.1.2 Experimental plasma jet and plasma processing procedure:

Experiments have been carried out with Atmospheric pressure plasma designed in National Centre for Plasma Sciences and Technology. (NCPST) in Dublin City University (figure 1). COP films, which were cut into small pieces of about 2.5 × 2.0 cm size. The inter-electrodes gap was maintained 2 mm in all experiments. AC high voltage power supply source was used to generate the desired air plasma. The voltage and current were measured using a high voltage probe (Tektronix P 6015A, 1000X) and current transformer. (2024, 200MHz digital oscilloscope Tektronix tds) was used to measure the voltage and current waveforms.

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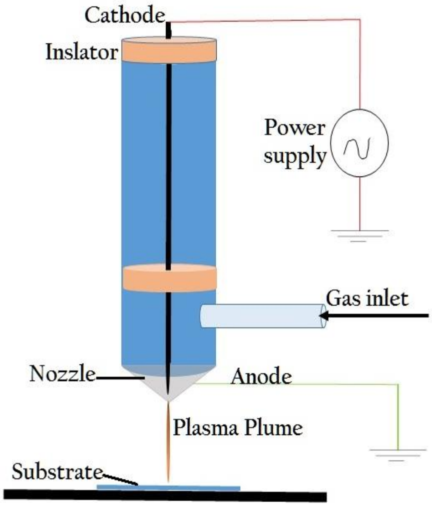

Figure (1): Schematic diagram of atmospheric pressure plasma jet used

The study was conceived on the basis of historical data design available in Design-Expert V12 software. The input variables parameters of plasma jet are power (input voltage, frequency), gas flow rate of the fed gas, and the distance to the sample from the plasma jet nozzle. The experiment process runs have been carried out by modifying one of the process parameters at a time to identify a range of each parameter. Lack of surface wettability of clear polymers. Figure 2 shows the water contact angle of the COP samples treated with air APPJ (14.5°) and untreated COP surface (96°). The method parameters, actual values are shown in Table 1. The code of variables and for the design matrix as shown in Table 2, statistical software Design-Expert V12 has been used. Historical data design was employed and for the experimental data; Polynomial Eq. (2) the regression equations were fitted for all responses to the experimental data. For each regression equation the statistical significance of the terms was checked using the sequential F-test, the in adaptive test and other adequacy measures with the same software to obtain the best fit.

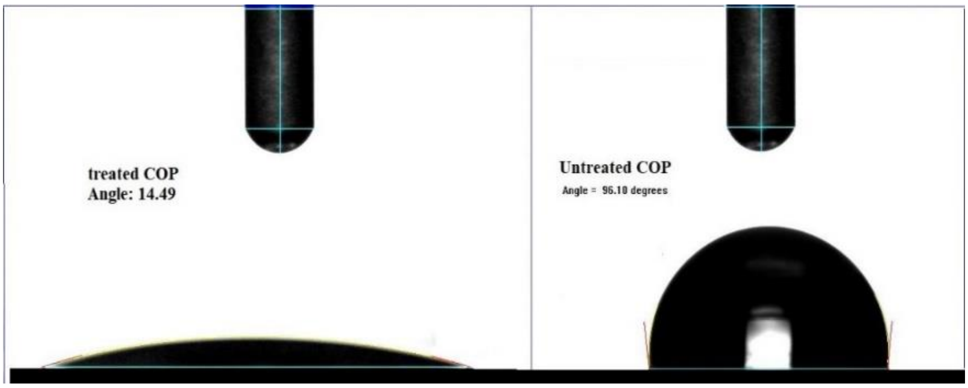

Figure (2): presents the water contact angle of untreated and air APPJ treated selected samples of COP

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Table 1: Independent variable and experimental design levels used

Variable	Unit	Limits
Input Voltage	V	155-220
Frequency	KHz	20-40
Air Flow	L\min	5-25
Distance	mm	25

2.1.3 Desirability approach

Several statistical techniques are available to solve multiple response problems, such as overlaying the contours plot for each answer, restricted optimization problems, and desirability approach. Because of its simplicity and flexibility in the system, the desirability approach is recommended and offers consistency in weighting and importance for individual response. Using this approach to solve these multiple response optimization problems involves using a technique for combining multiple responses into a dimensionless performance metric called the overall desirability function. The desirability method involves transforming each estimated response, Y_i, into an unitless utility with a limit of 0< di <1, where a higher di value implies that the response value Yi is more desirable if di= 0 means a fully undesirable response (Myers, Montgomery, & Anderson-Cook, 2016). In the current work, the individual desirability of each response, di, was calculated using Eqs. (3 -7). The shape of the desirability function can be changed for each goal by the weight field 'wt_i. Weights are used to give more emphasis to the upper/lower bounds or to emphasize the target value,

For goal as a maximum, the desirability will be defined by

$$di = \begin{cases} 1 & , \quad Y_i \le Low_i \\ \left(\frac{Y_i - Low_i}{High_i - Low_i}\right)^{wt_i} & , \quad Low_i < Y_i < High_i \\ 0 & , \quad Y_i \ge High_i \end{cases} \quad . \qquad (3)$$

For goal as a minimum, the desirability will be defined by

$$di = \begin{cases} 1 & , \quad Y_i \le Low_i \\ \left(\frac{High_i - Y_i}{High_i - Low_i}\right)^{wt_i} & , \quad Low_i < Y_i < High_i \\ 0 & , \quad Y_i \ge High_i \end{cases} \quad . \qquad (4)$$

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For goal as a target, the desirability will be defined by

$$di = \begin{cases} \left(\frac{Y_i - Low_i}{T_i - Low_i}\right)^{wt_{1i}} & , Low_i < Y_i < T_i \\ \left(\frac{Y_i - High_i}{T_i - High_i}\right)^{wt_{2i}} & , \ T_i < Y_i < High_i \\ 0 & , \ \text{Otherwise} \end{cases} \quad . \qquad (5)$$

For goal within range, the desirability will be defined by

$$di = \begin{cases} 1 & , \ Low_i < Y_i < High_i \\ 0 & , \ Otherwise \end{cases} \quad . \qquad (6)$$

$$D = \left(\prod_{i=1}^{n} d_i^{\,r_i}\right)^{1/(\Sigma r_i)} \quad . \qquad (7)$$

2.2 Optimization

The optimization element of Design-Expert software V12 searches for a combination of factor rates that simultaneously satisfy the requirements put on each of the responses and process factors (i.e. several-response model) (i.e. optimization requirements). In this work, numerical and graphical methods of optimisation were used by choosing the desired goals for each factor and response. As described before the process of numerical optimisation requires integrating the objectives into an overall desirability function (D). In the design-expert package, the numerical optimization functionality seeks one or more points in the factor domain that would maximize the objective function. The system defines regions in a graphical optimization with multiple answers, where parameters fit the proposed criteria simultaneously. A contour plot may also define the superimposition or overlaying of critical response contours. Instead, it becomes possible to search visually for the best compromise. It's suggested to run numerical optimization first in case of dealing with many responses; otherwise it might be impossible to find a feasible region. The graphical optimization displays the region in factor space of the feasible answer values. Regions which do not meet the criteria for optimisation are shaded. Figure.3 Displays the flow chart of the design-expert program optimisation process.

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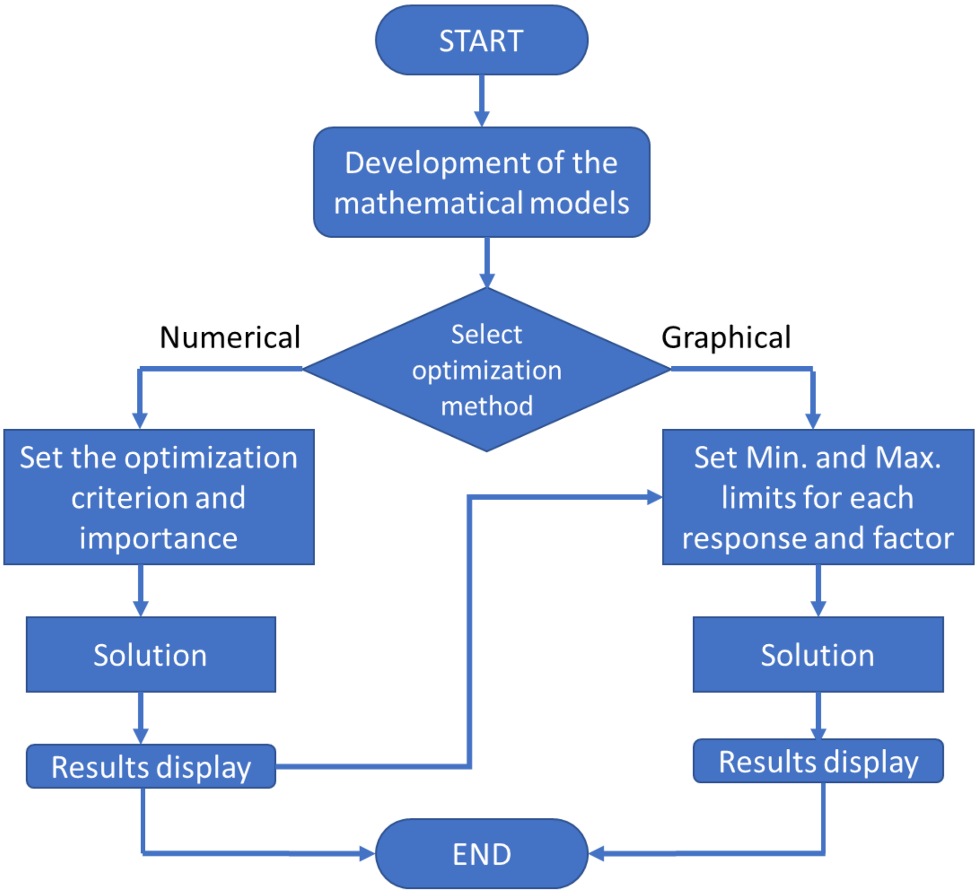

Figure (3): Optimization steps (Benyounis, Olabi, & Hashmi, 2008).

2.2.1 Experimental work

Experiments have been carried out with COP films in room temperature 21-23 C° and 50-70% humidity. The outer electrode (nozzle) is grounded while Radio Frequency (RF) power (50- 100W) 20-40 KHz is applied to the central electrode that creates a discharge. The reactive species generated exits the nozzle at high velocity and attains to the area that is to be treated. The electrode is placed horizontally inside the plastic cylinder. The atmospheric pressure plasma jet (APPJ) is produced between the electrode and the grounded cone when applying a high voltage in the presence of gas flow. There are many factors are playing in the value of applying power to produce APPJ Such as the power, frequency, air flow rate and distance between the nozzle and the treated .

2.2.2 Operating cost calculation

Atmospheric pressure plasma jet operating costs can be estimated per sample. The APPJ system used in this work utilized air gases of flow rate between 5 and 25 l/min. The compressor tank capacity is 24 litter and it consume 300 W to fill it up, so 1 litter cost 12.5 Watt. The power supply consumption depending in input voltage and frequency, to calculate the electricity we use a voltammeter and ammeter and calculate the power for every run. The operating cost calculation does not consider the system hardware, such as the power supply, the variac voltage controller and the nozzle. The total approximated operating cost per treated sample is given by Eq. (8).

$$\text{Treatment cost} = \frac{(\,(Plasma\ power + air\ compressor\ power) \times 250)/1000[KW]}{\left[60\frac{min}{h}\right]} \times 0.2$$

(€/sample). ………………………………. (8)

Where 250 is the sample dots covered by plasma plume, and 0.2 is kilowatt price.

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Table 2: Design matrix

	Factor 1 (A)	**Factor 2 (B)**	**Factor 3 (C)**	**Factor 4 (D)**		**Factor 1 (A)**	**Factor 2 (B)**	**Factor 3 (C)**	**Factor 4 (D)**
Run	Input Voltage	Frequency	Air Flow	**Distance**	Run	Input Voltage	Frequency	Air Flow	Distance
	V	KHz	L/min	mm		V	KHz	l/min	mm
1	220	35	5	3	**21**	175	20	20	5
2	220	35	10	3	**22**	175	30	20	5
3	220	35	15	3	**23**	175	40	20	5
4	220	35	20	3	**24**	175	20	10	5
5	220	35	25	3	**25**	175	30	10	5
6	220	20	20	5	**26**	175	40	10	5
7	220	30	20	5	**27**	155	40	10	25
8	220	40	20	5	**28**	175	35	20	25
9	155	35	20	3	**29**	155	35	10	20
10	175	35	20	3	**30**	155	35	20	20
11	210	35	20	3	**31**	175	35	20	20
12	155	20	20	3	**32**	175	35	10	20
13	155	30	20	3	**33**	155	35	20	15
14	155	40	20	3	**34**	155	35	10	15
15	210	35	20	25	**35**	175	35	20	15
16	210	35	20	20	**36**	175	35	10	15
17	210	35	20	15	**37**	155	35	10	10
18	210	35	20	10	**38**	155	35	20	10
19	210	35	20	5	**39**	175	35	20	10
20	210	35	20	3	**40**	175	35	10	10

Table 3: Experimentally measured responses.

	Response 1	**Response 2**		**Response 1**	**Response 2**
Run	Water contact angle	Cost\sample	**Run**	Water contact angle	Cost\sample
	°	€/sample		°	€/sample
1	33.28	0.099	**21**	35.44	0.240
2	28.45	0.151	**22**	23.8	0.241
3	18.62	0.203	**23**	20.37	0.244
4	8.98	0.255	**24**	39.81	0.136
5	8.93	0.307	**25**	29.01	0.137
6	39.81	0.245	**26**	22.27	0.140
7	29.01	0.250	**27**	69.22	0.134
8	22.3	0.255	**28**	68.33	0.244
9	20.71	0.238	**29**	54.58	0.134
10	18.77	0.244	**30**	42.74	0.238
11	17.54	0.250	**31**	43.88	0.244
12	32.1	0.236	**32**	48.59	0.140
13	32.5	0.237	**33**	37.3	0.238
14	22.64	0.238	**34**	39.38	0.134
15	62.16	0.250	**35**	38.15	0.244
16	42.96	0.250	**36**	39.23	0.140
17	38.87	0.250	**37**	40.47	0.134
18	26.85	0.250	**38**	36.54	0.238
19	19.34	0.250	**39**	27.6	0.244
20	12.73	0.250	**40**	32.84	0.140

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3 RESULTS AND DISCUSSION

3.1 Development of mathematical models

The fit summary tab in the design-expert program shows the highest order polynomial where the additional terms are important and the model is not aliased. Selecting a step-by-step regression method automatically eliminates insignificant model terms. The sequential F-test for the importance of both the regression model and the individual model terms, together with the lack of fit testing, was performed using the Design-Expert V12 software. The Analysis of Variance (ANOVA) for the reduced quadratic models summarizes the study of each answer and indicates the significant model terms. Tables 4 demonstrate the ANOVA findings for the water contact angle and operating costs, respectively. Certain adequacy measures R^2, Adjusted-R^2 and predicted-R^2 are also shown in the same tables. All the appropriateness measures are in logical agreement and indicate a significant relationship. In all cases, the appropriate precision ratios are greater than 4 indicating appropriate model. The analysis of the variance result for the water contact angle model shows that the main effective parameter of the APPJ is the distance followed by the frequency then the air flow. However, the ANOVA finds that there is no significant effect of the input voltage but when interaction with the power supply frequency it become significant, so, the input voltage was introduced to support the hierarchy. Moreover, there is another interaction effect between the in voltage and the air flow rate, are significant model terms; however, the main effect of input voltage was introduced to support the hierarchy.

The **Predicted R^2** of 0.9140 is in reasonable agreement with the **Adjusted R^2** of 0.9288; i.e. the difference is less than 0.2.

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Table 4:. ANOVA analysis for the water contact angle model

Source	Sum of Squares	V	Mean Square	F-value	p-value	
Model	7974.03	7	1139.15	73.73	< 0.0001	significant
A-Input Voltage	5.32	1	5.32	0.3442	0.5615	
B-Frequency	991.77	1	991.77	64.19	< 0.0001	
C-Air Flow	412.37	1	412.37	26.69	< 0.0001	
D-Distance	5594.54	1	5594.54	362.08	< 0.0001	
AB	157.35	1	157.35	10.18	0.0032	
AC	97.62	1	97.62	6.32	0.0172	
D^2	250.35	1	250.35	16.2	0.0003	
Residual	494.44	32	15.45			
Lack of Fit	482.87	31	15.58	1.35	0.6046	not significant
Pure Error	11.57	1	11.57			
R^2=0.942			Adjusted R^2=0.929			
Predicted R^2=0.914			Adeq Precision=32.626			

Table 5: ANOVA analysis for the operating cost model

Source	Sum of Squares	V	Mean Square	F-value	p-value	
Model	1.93	5	0.3858	241.5	< 0.0001	significant
A-Input Voltage	0.7356	1	0.7356	460.41	< 0.0001	
B-Frequency	0.1305	1	0.1305	81.68	< 0.0001	
C-Air Flow	0.0007	1	0.0007	0.441	0.5111	
AB	0.0373	1	0.0373	23.32	< 0.0001	
AC	0.0048	1	0.0048	3.01	0.0917	
Residual	0.0543	34	0.0016			
Lack of Fit	0.0543	33	0.0016			
Pure Error	0	1	0			
Cor Total	1.98	39				
R^2=0.9726			Adjusted R^2=0.9686			
Predicted R^2=0.9632			Adeq Precision=44.8087			

Nonetheless, the APPJ modified COP wettability parameters have variables effect on COP water contact angle. From the results the main effect of the four factors was the distance then the frequency then the air flow rate after that quadratic effect of distance and the less affect factor was the input volte. Nevertheless, the main effect of input plasma jet voltage was added to support hierarchy. The analysis of variance results in the plasma polymers modification operation cost model Table 5 showed that the main effect of the input volte and frequency along with the air flow are significant model terms. As mentioned above, treatment costs per sample can be calculated using Eq. (9). In this work, a mathematical model was built to estimate optimization costs. Based on the results obtained, the models developed are statistically accurate and can be used for further analysis. The final models for coded and actual factors are shown below the Eq. (10).

3.1.1 Final Equation in Terms of Actual Factors

Water contact angle = -65.12818+0.711230* Input Voltage+2.05493* Frequency+1.76937* Air Flow +0.179582*Distance-0.01651* Input Voltage* Frequency-0.01297 Input Voltage* Air Flow+0.06294*Distance^2. ………………………………………………………….……………… (.9)

Cost sample = 0.74838+0.00126* Input Voltage-0.03571* Frequency+0.01725* Air Flow+0.00025* Input Voltage* Frequency. ………………. (10)

3.2 Effect of process parameters on the responses

In the subsequent headings, whenever an interaction effect or a comparison between any two input parameters is being discussed the other two parameters would be on their levels mentioned in the caption.

3.2.1 Water contact angle

It is evident from the results that all the process input parameters have a significant effect on water contact angle of an APPJ. However, Figure 4 is a perturbation plot which illustrates the effect of the plasma parameters on the water contact angle. The distance (D) has a positive effect on the water contact angle and the other factors have a negative effect. Both the frequency and the air flow have a negative effect on the impact water contact angle. While, in the case of the distance the result demonstrates that increasing distance leads increasing the water contact angle.

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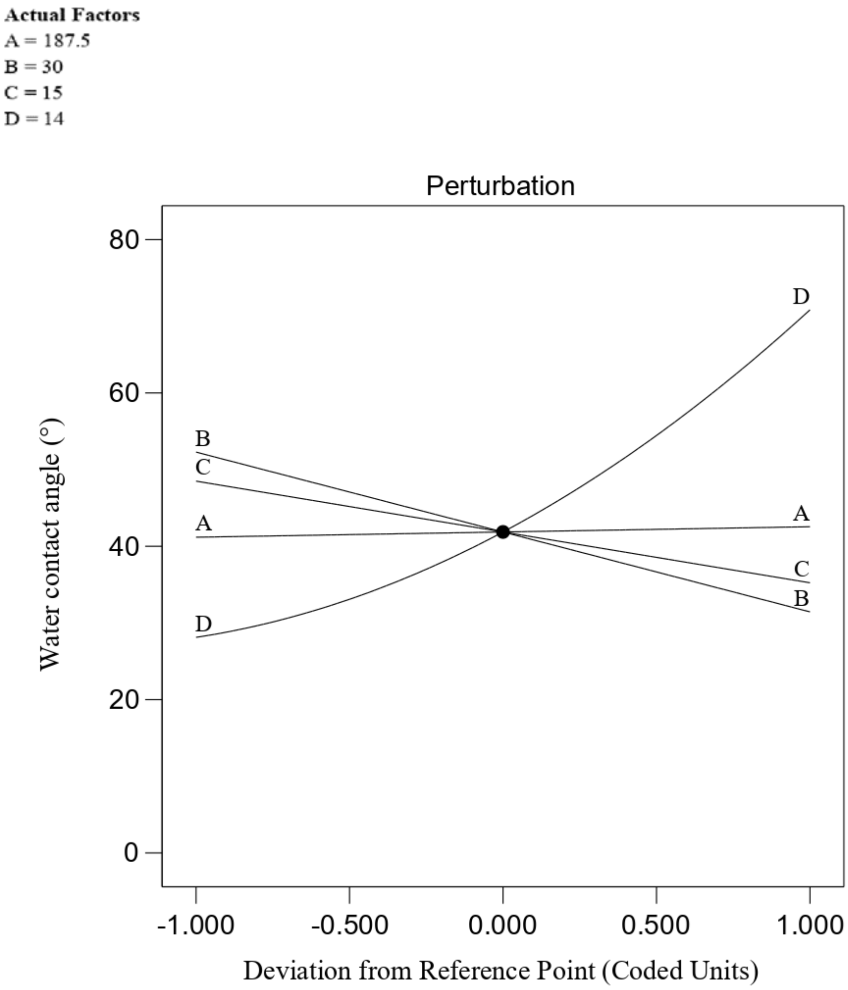

Figure (4): Perturbation plot showing the effect of all factors on the COP water contact angle.

Figure. 5-A is Contours plot plot showing the frequency and the input voltage on water contact angle at Air flow of 5 l/min and distance of 3 mm. It is evident from this plot A that at frequency range of 20-27.5KHz when increasing the input voltage that would lead to slight increase in the contact angel. At 27.5 KHz frequency the water contact angle remains at the same value for any input voltage, for higher power supply frequency the COP water contact angle decrease gradually when increasing the input voltage. The same behaviour is observed in figure 5-B at air flow 10 l/min and distance 20 mm, the difference is at 35.5 KHz frequency the water contact angle remains at the same value at any input volte value Then decreased with increasing the input volt. This could be related to that fact that heavily depends on plasma frequencies and a correlation with of the plasma active species.

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The plasma operating parameters such as frequency has an effect on the surface activation because of the active species generated which reflect on the polymers surfaces wettability(Rinsch et al., 1996; Van Deynse, Cools, Leys, De Geyter, & Morent, 2015).. However, when using a frequency above this threshold approximately 27 and 35.5 KHz (in our examples) a more desirable contact angle could be achieved by applying a higher input voltage of 220 V. In the meantime, the smallest contact angel of about 7° could be obtained by using the highest frequency of 40 KHz and the highest input voltage of 220 V. This is due to the depends on other parameters, such as air flow rate and distance to the sample surface from the plasma nozzle (Van Deynse et al., 2015) and the active species concentration when changing the power supply parameters (O'Neill et al., 2012). Figure 6, depicts the effect of input voltage and frequency on the water contact angle; the higher the voltage, the lower the water contact angle. The water contact angle is clearly lower at high voltage applied (Abourayana & Dowling, 2015).

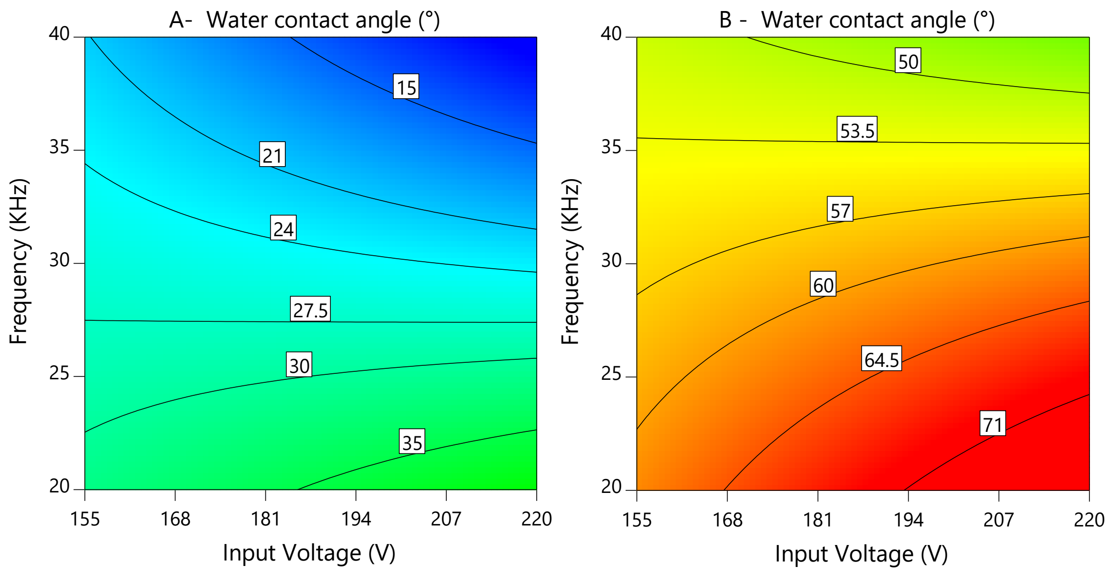

Figure (5): Contours plot showing the effect of input voltage V and frequency on the COP water contact angle (A) d=3mm and air flow=20 l/min. (B) d=20mm and air flow 10 l/min

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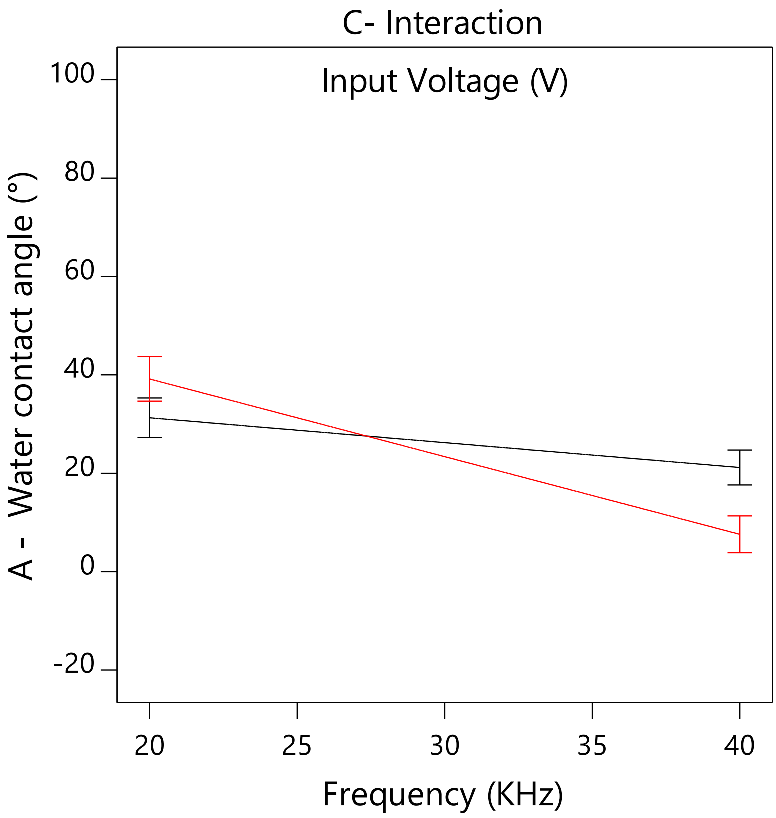

Figure (6); Interaction effect between input voltage and frequency on the water contact angle (Red line is high voltage and black line is low voltage)

Figure 7-A Shows the contours plot of the plasma input voltage and air flow rate at a distance of 15 mm and the power supply frequency of 20 KHz. At low flow rate the water contact angle is relatively lower at low input voltage and higher at higher input voltage. This is could be because of the gas temperature is reduced with the gas flow rate increasing as a result of convective cooling (Chen & Li, 2015)whereas, at high flow rate the water contact angle increases with increasing the input voltage. This observation can be ascribed to the greater incorporation of O groups with higher powers, as there have been no substantial changes in the surface ruggedness, the high Air flow provides intensive plasma particles while at low flow rate there are no enough particles (Fridman, 2008). Therefore, the gas flow rate must be sufficiently high to provide enough particles travelling toward the polymer surface. Figure 7-B shows the interaction between the air flow rate and the input voltage at 5 l/min (black) and high flow rate 25 l/min (red). From the figure as mentioned before in (Van Deynse et al., 2015) , it is evident that at high air flow rate the water contact angle is lower.

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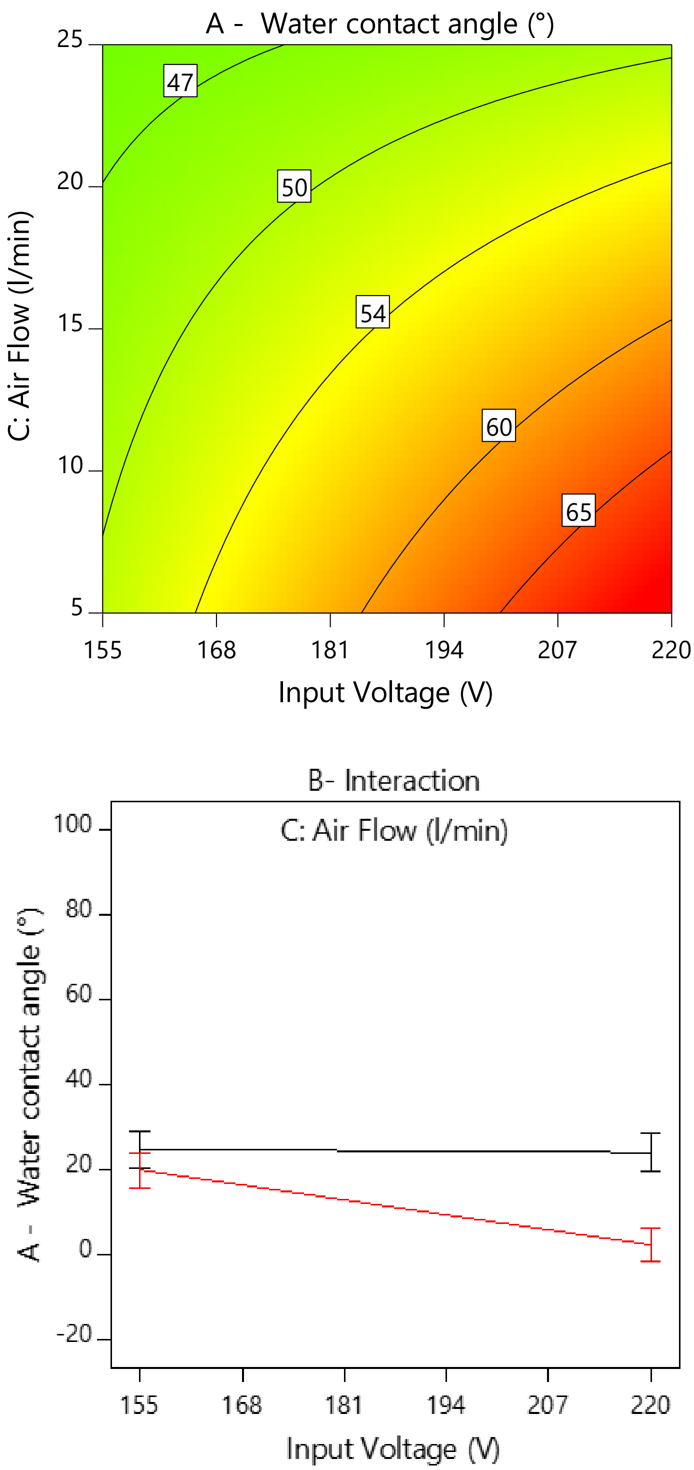

Figure (7): (A) Contours plot and (B) Interaction showing the effect of input voltage and air flow on the water contact angle

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3.2.2 Impact on cost.

Figure 8, shows the interaction effect among the parameters within the investigated range, where. It can be seen that input voltage, has the strongest positive effect on the cost. Changing the volt from the minimum to maximum values has increased the response by 31.25%. The frequency has a moderate effect. Changing the frequency B has proportionally increased the cost by 15.75%. the air flow C has a very little effect on the cost.

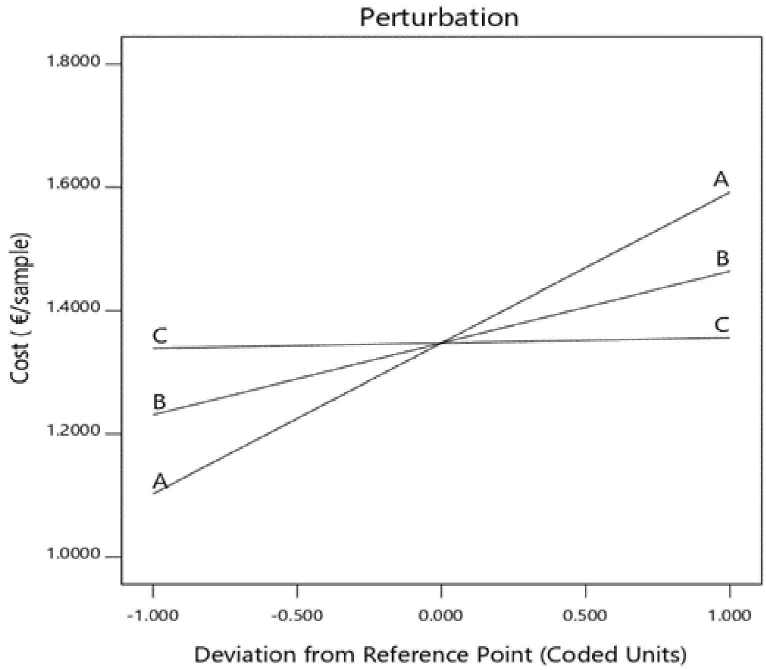

Figure (8): Perturbation plot showing the effect of all factors on the COP surface modification cost

4 OPTIMIZATION

The issue of linking between the surface wettability and treatment cost must be addressed as any increase in the surface wettability is usually reflected in increase of the cost as a consequence both are usually studied together. On balance, and based on the above discussion, it is better to run an optimization study to find out the optimal wettability conditions at which desirable cost of the treatment can be achieved. In fact, once the models have been developed and checked for adequacy, the optimization criteria can be set to find out the optimum water contact angle conditions. In this investigation, two criteria were implemented to minimize both the water contact angle and the cost per sample. The first criterion is to reach minimum the water contact angle and no limitation on either the process parameters or the operating cost as shown in table 6. While, table 7. shows the second criterion, the goal was to reach minimum the water contact angle with relatively low-operating cost

Table 6: Optimal solution as obtained by design-expert based on the first criterion

No	Voltage	Frequency	Air Flow	Distance	WCA	Desirability	
1	209.0	39.74	24.8	3.8	6.25	1	Selected
2	218.4	36.60	24.4	3.4	8.77	1	
3	216.8	38.34	24.9	4.6	6.72	1	
4	202.9	39.83	24.7	3.4	7.59	1	
5	217.6	39.38	23.7	6.5	7.80	1	
6	209.5	39.63	23.2	3.3	7.43	1	
7	206.0	39.71	23.9	4.3	8.18	1	
8	201.4	39.94	24.2	3.2	8.14	1	
9	212.0	39.87	21.9	4.5	8.58	1	
10	219.4	36.09	24.7	3.2	8.87	1	

Table 7: Optimal solution as obtained by design-expert based on the second criterion

No	Voltage	Frequency	Air Flow	Distance	WCA	Cost/sample	Desirability	
1	155.0	40.0	25.00	3.0	19.97	1.17	0.83	Selected
2	155.0	40.0	24.90	3.0	19.99	1.17	0.82	
3	155.0	40.0	24.63	3.0	20.06	1.17	0.82	
4	155.0	40.0	24.52	3.0	20.10	1.17	0.82	
5	155.0	40.0	24.38	3.0	20.13	1.17	0.82	
6	155.0	40.0	24.23	3.0	20.16	1.17	0.82	
7	155.0	40.0	23.97	3.0	20.22	1.17	0.82	
8	155.0	39.8	25.00	3.0	20.06	1.17	0.82	
9	155.1	39.9	24.39	3.0	20.14	1.17	0.82	
10	155.0	40.0	23.65	3.0	20.30	1.17	0.82	

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5 CONCLUSION

Using the Plasma jet within the changing of the parameters considered in this study the following points can be concluded:

1. Historical data is an accurate technique to optimize the atmospheric pressure plasma jet process in order to obtain the best surface wettability of the polymers surface.
2. An input voltage between 200 and 220 V is an optimum input to obtain an excellent water contact angle and its interaction with the frequency. The distance is the most effective plasma jet parameter.
3. The graphical optimization results allows quicker search for the optimal surface treatment settings.
4. The plasma surface treatment operating cost can be reduced by approximately 30% with acceptable surface wettability if the optimal APPJ conditions are used. The R2 value of about 0.9140 indicates that about 91.4% of the variability in the data is explained by the model. This fact combined with the satisfactory residual analysis further indicates that the model is a very good fit to the data and that the COP surface water contact angle, within the investigated range of parameters, can be predicted. This model will be able to, theoretically, predict the wettability of the sample; and this will be useful in comparing the experimental model to the theoretical model.

References

- Abourayana, H. M., & Dowling, D. P. (2015). Plasma processing for tailoring the surface properties of polymers. *Surface Energy,* , 123.
- Agulló-López, F., Climent-Font, A., Muñoz-Martín, Á, Olivares, J., & Zucchiatti, A. (2016). Ion beam modification of dielectric materials in the electronic excitation regime: Cumulative and exciton models. *Progress in Materials Science, 76,* 1-58.
- Benyounis, K. Y., Olabi, A., & Hashmi, M. (2008). Multi-response optimization of CO2 laser-welding process of austenitic stainless steel. *Optics & Laser Technology, 40*(1), 76-87.
- Chen, C., & Li, S. (2015). Spectroscopic measurement of plasma gas temperature of the atmospheric-pressure microwave induced nitrogen plasma torch. *Plasma Sources Science and Technology, 24*(3), 035017.
- Dowling, D. P., O'Neill, F. T., Langlais, S. J., & Law, V. J. (2011). Influence of dc pulsed atmospheric pressure plasma jet processing conditions on polymer activation. *Plasma Processes and Polymers, 8*(8), 718-727.
- Fridman, A. (2008). *Plasma chemistry* Cambridge university press.
- Hansen, M. H., Finlayson, M. F., Castille, M. J., & Goins, J. D. (1993). The role of corona discharge treatment in improving polyethylene-aluminum adhesion: An acid-base perspective. *Tappi Journal, 76*(2), 171-177.
- Khuri, A. I., & Cornell, J. A. (2018). *Response surfaces: Designs and analyses* Routledge.
- Kim, K. N., Lee, S. M., Mishra, A., & Yeom, G. Y. (2016). Atmospheric pressure plasmas for surface modification of flexible and printed electronic devices: A review. *Thin Solid Films, 598,* 315-334.
- Kostov, K. G., Nishime, T. M. C., Castro, A. H. R., Toth, A., & Hein, Luis Rogerio de Oliveira. (2014). Surface modification of polymeric materials by cold atmospheric plasma jet. *Applied Surface Science, 314,* 367-375.
- Lohr, S. L. (2019). *Sampling: Design and analysis: Design and analysis* Chapman and Hall/CRC.
- Merenda, A., Ligneris, E., Sears, K., Chaffraix, T., Magniez, K., Cornu, D., . . . Dumee, L. F. (2016). Assessing the temporal stability of surface functional groups introduced by plasma treatments on the outer shells of carbon nanotubes. *Scientific Reports, 6,* 31565.